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Problems Related to the Organisation of a Laboratory for Non-Destructive Testing and Selected Destructive Tests

Abstract: Increasing demands for NDT services trigger organising and opening laboratories specialising in such testing and provided with the necessary equipment. This was the reason for the determination of testing means and costs necessary for performing NDT activities. Information collected and presented in this article should optimise the creation of a laboratory in terms of necessary equipment and investment costs.

Keywords: non-destructive testing, laboratory organisation,procedures, equipment

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Introduction

Industrial products (e.g. fusion or pressure welded, cast, forged etc.) should be characterised by the quality required or accepted by customers. To this end, in addition to organisation-related activities, many various non-destructive testing (NDT) methods are used. This results in growing demands for NDT-related services, which in turn leads to the opening of laboratories specialising in performing such services and possessing necessary equipment. As available publications contain very little information on the subject, it has become necessary to define testing means necessary for given NDT methods as well as to determine related costs. Information collected should optimise the organisation of an NDT laboratory in terms of necessary equipment and investment costs. This, in turn, should facilitate the creation of a professional testing centre successfully competing in the difficult market of NDT services.

The equipment and cost-related analysis involved five basic NDT methods, i.e. visual testing (VT), penetrant testing (PT), magnetic particle testing (MT), radiographic testing (RT) and ultrasonic testing (UT) [1]. The analysis also included the equipment and cost of metallographic tests and hardness tests frequently used and required at different testing stages. The analysis was performed having mainly tests of welded joints in view as joining materials by means of welding technologies dominates the market of structures made both for industrial and individual users.

Characteristics of Planned and Unplanned Non-Destructive and Destructive Tests

The basic NDT method used for all types of structures is visual testing. Visual tests of welded joints include accurate observation of joint surfaces (both from the weld face and root, if accessible) and simple measurements of detected surface imperfections (Fig. 1). Visual tests

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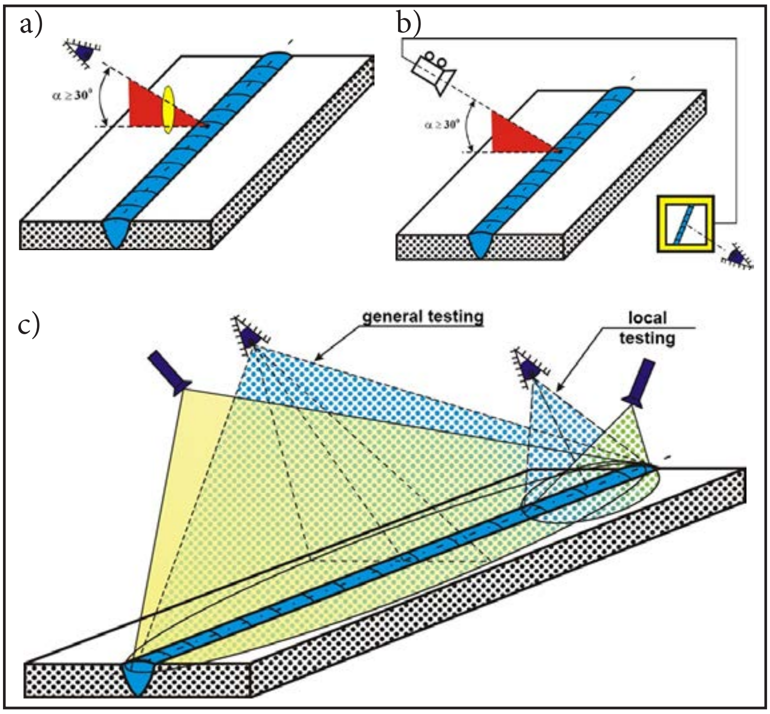

Fig. 1. Visual tests of welded joints: a) direct, b) remote, c) direct: general (l>600 mm, α≥30°, E≥160lx), local (l≤600 mm, α≥30°, E≥500lx)

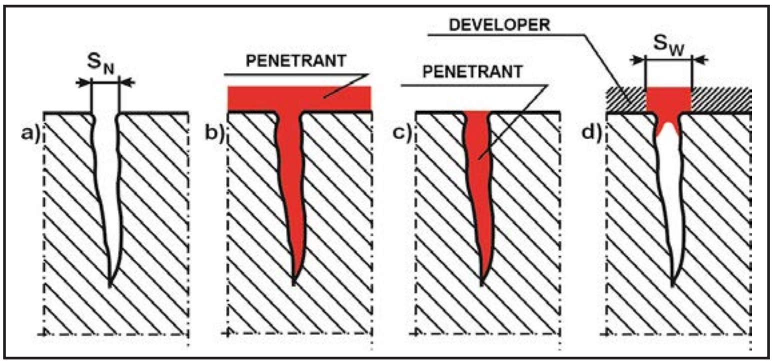

Fig. 2. Basic phases of penetrant testing: a) preparation and initial cleaning of a surface, b) applying a penetrant and saturating discontinuities, c) removal of excess penetrant from asurface, d) applying a developer and revealing discontinuities; S_N – discontinuity width, S_w – indication width

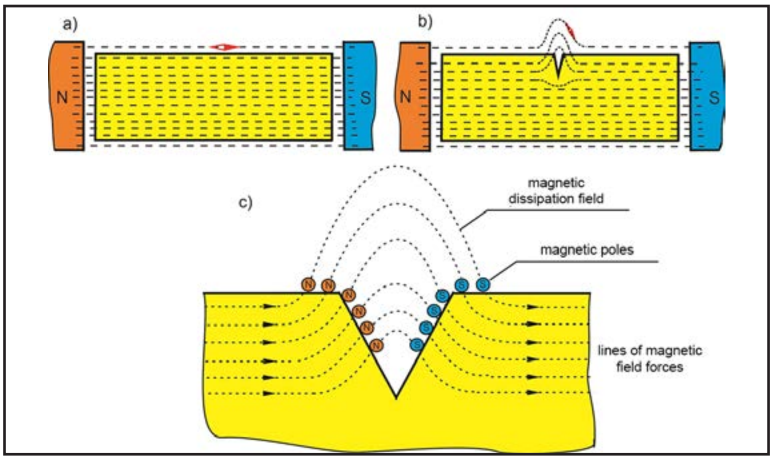

Fig. 3. Generation of a dissipation magnetic field: a) lines of magnetic field forces in an object without discontinuities, b) lines of magnetic field forces in an object with a surface discontinuity, c) configuration of a dissipation magnetic field

are regarded as the simplest, cheapest and often the most effective way of controlling welded products.

Penetrant testing is usually performed after visual testing of a given product and follows the removal of unacceptable imperfections from its surface. Penetrant tests use the phenomenon of capillarity, i.e. penetrant liquids first entering narrow spaces and next being removed using developers. In this manner, indications in the form of coloured (e.g. red) or illuminated (using UV radiation) spots or lines subject to assessments (Fig. 2).

Magnetic particle testing of a joint (object) involves generating a magnetic field and searching for so-called local magnetic fields of dissipation or residual magnetism formed above the surface in areas where material discontinuities are present or in areas remaining in direct vicinity of material discontinuities (Fig. 3). In this method, finer-grained ferromagnetic powder is used for detecting magnetic field interference. Radiographic testing utilises the ability of ionising radiation (usually X-ray (X) or gamma (γ)) radiation) to penetrate

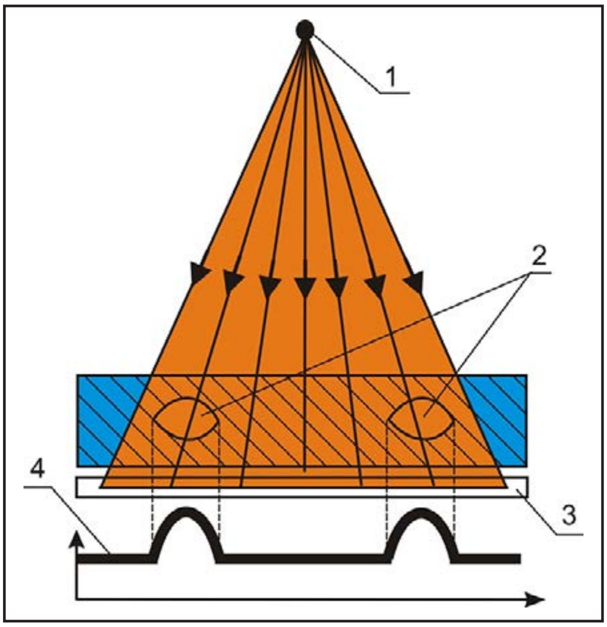

Fig. 4. Recording of material discontinuities on a radiographic film: 1: source of radiation, 2: material discontinuities (imperfections), 3: cassette with a radiographic film, 4: change of optical density on a film

the matter. The radiation is recorded on a radiographic film (Fig. 4).

Radiation passing through a discontinuity is less weakened, thus radiation reaching the film is of a higher intensity and causes greater blackening of the film. After photochemical processing of the exposed film, an image is obtained presenting imperfections in the form of spots or lines whose blackening differs from the background. This image is subjected to an analysis. Ultrasonic testing utilises phenomena accompanying the propagation of acoustic waves having a frequency higher than the upper limit of human ear audibility (over 16 kHz). An object is exposed to ultrasonic waves and impulses generated by these waves while passing through the object are detected. Impulses, i.e. amplitude, phase, spectrum or impulse envelope, obtained while moving an ultrasonic head around or along a discontinuity provide information about the presence of the discontinuity (Fig. 5).

Detecting discontinuities in ultrasonic tests is based on the following methods: echo method – consisting in the reflection of waves from the object surface and discontinuities, shadow method (shadowing) – consisting in stopping down a beam of waves by discontinuities and resonance method – consisting in generating a standing wave (in a material being tested), resonating with a wavelength. In addition, the shadow method utilises a tandem technique, whereas TOFD method is used while testing welded joints.

Metallography is a field of metal science (i.e. science of metals and their alloys) focused on examining metal structures. Metallographic tests belong to destructive tests as their performance is connected with disturbing the continuity of (i.e. damage to) the product being tested. In general, metallographic tests are divided into macro and microscopic.

Macroscopic tests consist in naked eye observations or low magnification observations (up to approximately 25-30 times though some authors claim up to approximately 50 times) of an appropriately prepared cross-sectional surface or of a fracture of an element being tested (Fig. 6). Microscopic tests are usually performed using optical metallographic microscopes within magnifications ranging from approximately 30 to 2000 times (Fig. 7).

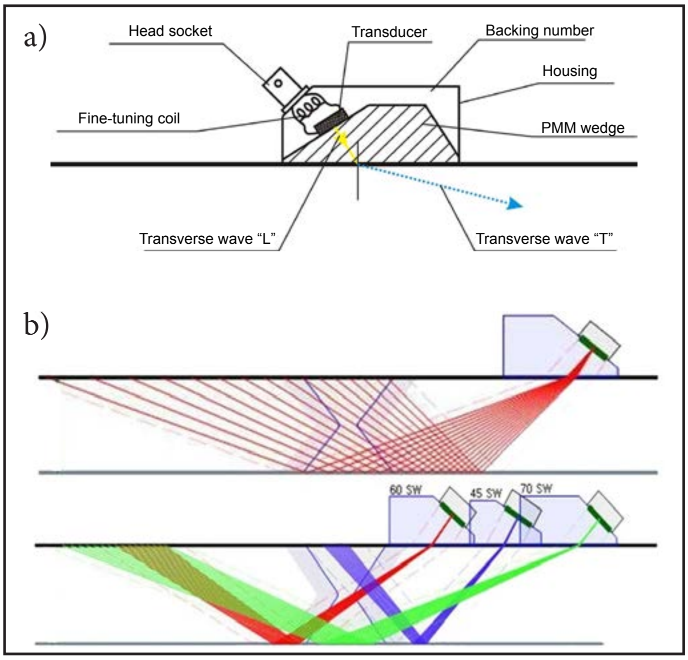

Fig. 5. Scheme of design and operation of:
a) ultrasonic slant head, b) mosaic transducer

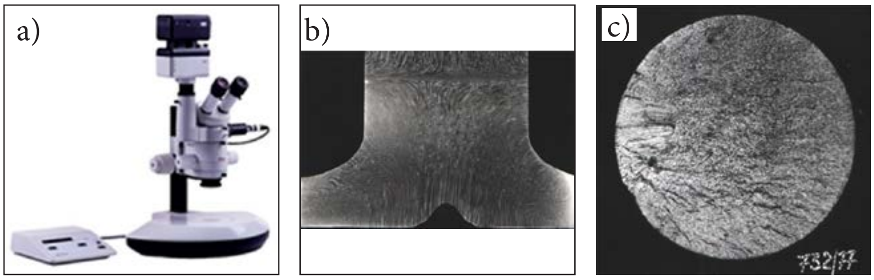

Fig. 6. Examples of a) microscope for macroscopic tests(photo by Leica Microsystems), b) macrostructure of a friction-welded joint, c) fatigue fracture of a friction-welded roller

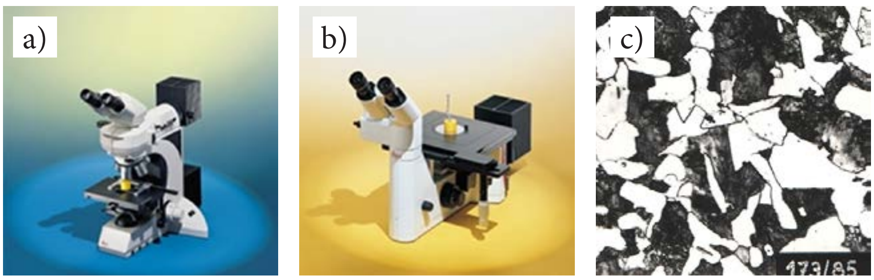

Fig. 7. Examples of a) simple optical metallographic microscope (photo by Leica Microsystems), b) inverted optical metallographic microscope (photo by Leica Microsystems), c) microstructures of C45 steel

Greater ranges of maximum magnifications than those obtained using optical microscopes are available for users of scanning electron microscopes (SEM), which offer magnifications of tens of thousands of times. Even greater magnifications are possible using high-resolution transmission electron microscopes (TEM).

Hardness tests consist in pressing an indenter into a material being tested until plastic strains are formed. Thus, hardness is a measure of material resistance to plastic strains caused by the indenter. Testing methods are normalised and differ in indenter shapes and calculation methods. Testing methods usually used in research practice are those of Brinell, Vickers and Rockwell (Fig. 8).

Equipment and Costs

Depending on the testing methods applied, the equipment for testing the quality of welded joints can be very rich and diversified, and as a result, may entail huge investment costs. The remainder of this study presents equipment necessary for tests performed using individual methods along with average prices of equipment and machinery.

Visual Tests

As regards obligatory visual tests concerned with examining welded joints, a laboratory should be equipped with resources presented below, along with their typical prices (Table 1).

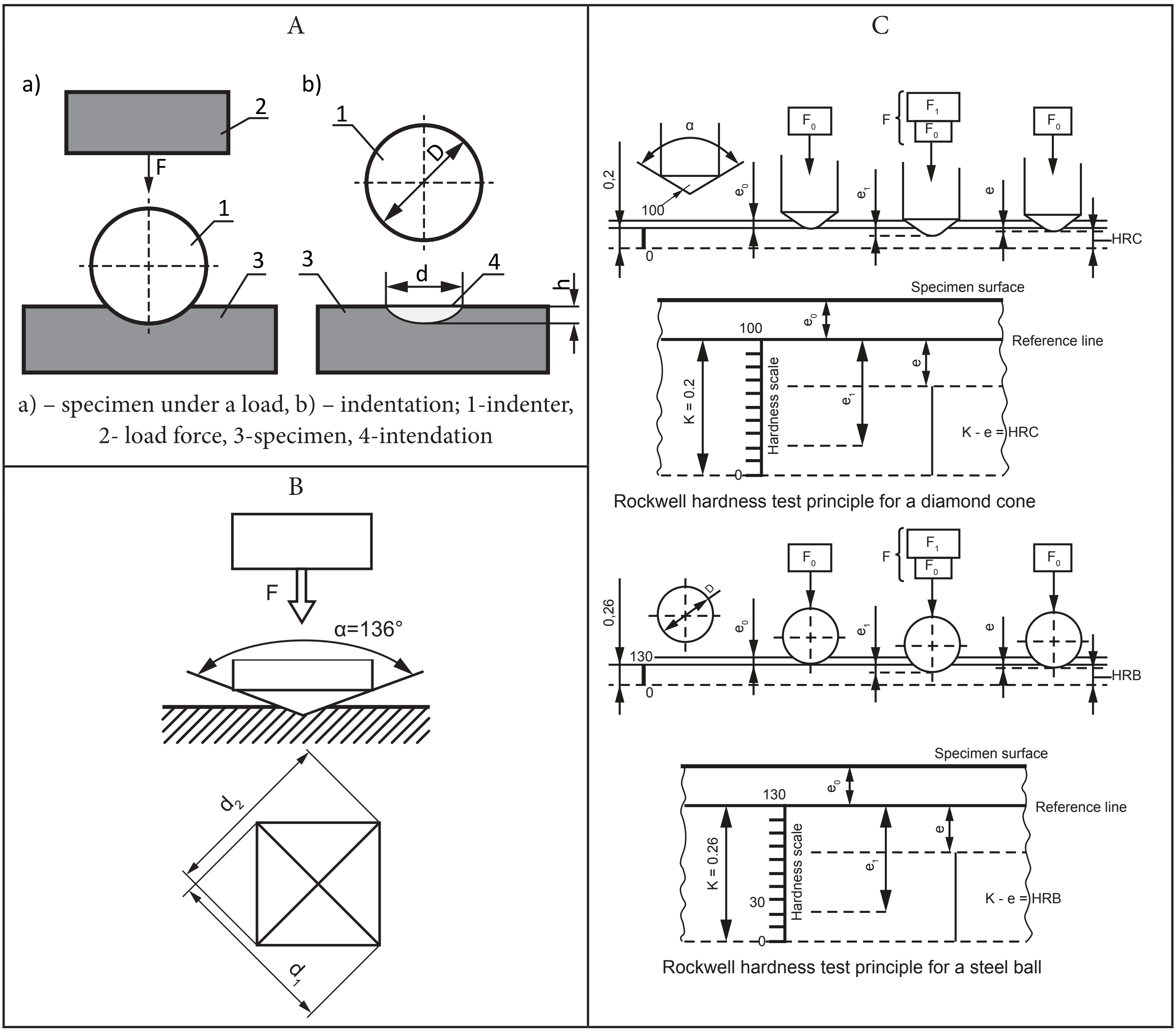

Fig. 8. Hardness tests using various methods: a) Brinell, b) Vickers, c) Rockwell

Table 1. Equipment for a visual testing laboratory and their costs

No.	Name of device or other equipment	Approximate cost (gross) 1 piece or set (PLN)
1	Universal weld gauge	150-200
2	Universal slide caliper	30-100
3	Magnifying glass (magnif. to approx. 4 times)	10-30
4	Magnifying glass (magnif. to approx. 10 times)	10-30
5	Straightedge ruler (2 – 3 m)	5-10
6	Workshop ruler (30 – 50 cm)	5-10
7	Torch for visual tests	300-500
8	Regular torch	20-50
9	Markers (indelible)	20-50
10	Wire brush (steel, brass, for aluminium, for high-alloy steel)	50-100
11	Luxmeter	1800-2200
12	Backlit inspection mirrors	800-2500
13	Digital photographic camera	800-1000
14	Rigid endoscope (borescope)	5000-8500
15	Flexible endoscope (fiberscope)	20000-30000
16	Videoscope with verification blocks and measurement software	60000-16000
	IN TOTAL	**89000-205280**

As can be seen in Table 1, the total cost of equipment for visual tests of welded joints is significant and restricted within a range of approximately 89 thousand PLN to approximately 205 thousand PLN. However, it should be noted that conventional visual testing requires equipment presented in items 1 through 11 [1, 2]. In such case, the cost of equipment is restricted within a range of approximately 2400 to approximately 3300 PLN. Providing a VT laboratory with inspection mirrors (item 12 in Table 1), recommended for observing poorly accessible areas, increases this cost by between approximately 30 and 70%.

Instead of a photographic camera (item 13) it is possible to record welding imperfections (or areas to be repaired) by sketching. In this way it is possible to save approximately 1000 PLN. However, a test report is significantly more accurate and easier when using a camera. It should also not be ignored that the aesthetics of a final test report is of significant importance both in relation to an ordering party as well as potential customers. Items 14-16 presented in Table 1 constitute special technologically advanced equipment characterised by the highest cost. For this reason, visual tests involving the use of such equipment should be subject to an additional contract. Nevertheless, a professional NDT laboratory should be in possession of at least one borescope. This means that the minimum cost of equipment for visual testing of welded joints (and of other products), depending on the class of equipment, is restricted within a range of approximately 9 thousand to approximately 15 thousand PLN.

Penetrant Tests

Due to the character of laboratory activity (services provided mainly outside, e.g. on construction sites), the use of equipment for local testing is recommended. For this reason, a laboratory should possess the equipment presented in Table 2 [3, 4].

Table 2. Equipment for a penetrant testing laboratory and their costs

No.	Name of device or other equipment	Approximate cost (gross) 1 piece or set (PLN)
1	Brush (soft, not leaving hair)	5-150
2	Magnifying glass (magnification up to 4 times)	10-30
3	Universal slide caliper	30-100
4	Straightedge ruler (gauge)	5-10
5	Stopper	50-100
6	Markers (indelible)	20-50
7	Absorptive and lint-free cloth	5-20
8	Paper towel	5-15
9	Wire brush	50-100
10	Sets of substances for dye penetration (penetrant, remover, developer)	80-140
11	Sets of substances for fluorescent penetration (penetrant, remover, developer)	100-150
12	Regular torch	20-50
13	Luxmeter	1800-2200
14	UV – A radiation source	5000-6700
15	UV A radiation meter	2500-3400
16	Digital photographic camera	800-1000
17	Personal protective equipment (protective clothing, boots resistant to chemicals, goggles, filters or respiratory tract protecting apparatus, gloves resistant to solvents)	1700-2500
18	Reference specimen no. 2	1800-2300
	IN TOTAL	**13980-19015**

As can be seen in Table 2, the equipment is very mobile as its handling and transport do not create any problems. It is highly recommended that the set of testing elements should be carried in a shock and damage-proof light (e.g. aluminium) portable case. As can be seen in Table 2, the total cost of equipment for penetrant tests is restricted within a range of approximately 14 thousand PLN to approximately 19 thousand PLN. However, it should be noted that the estimate does not include costs of a stationary stand for penetrant tests.

Magnetic-Particle Tests

Equipment for magnetic–particle tests, similar to that for penetrant testing, should be portable as it will be used mainly on location. Such a solution ensures mobility of service and increases competitiveness. For this reason, an MT laboratory should be provided with equipment presented in Table 3 [5, 6]. Equipment, devices and other means necessary for performing magnetic particle tests are presented in items 1 through 19. Therefore, the cost of testing equipment is restricted within a range of approximately 56 thousand PLN to approximately 74 thousand PLN. In this case, a photographic camera (item 20) can be regarded as a tool which can be used in other tests as well.

Radiographic Tests

In industrial practice, radiographic tests usually include X-raying or γ-raying, i.e. X-ray radiography and gamma-ray radiography. In on-site conditions (e.g. on a construction site), isotopic tests are usually applied. However, in welding procedure qualification processes, while qualifying welders, during inspections of critical structures etc., the use of radiographic equipment is required [7, 8, 9]. For this reason, it was necessary to determine what equipment would be needed in an X-ray laboratory and the costs of such an investment (Table 4).

Table 3. Equipment for a magnetic-particle testing laboratory and their costs

No.	Name of device or other equipment	Approximate cost (gross) 1 piece or set (PLN)
1	Wire brush, abrasive paper	50-100
2	Magnifying glass (magnification up to 4 times)	10-30
3	Universal slide caliper	3-100
4	Straightedge ruler (2 – 3 m)	5-10
5	Indelible markers	20-50
6	Spray for applying slurries	50-150
7	Priming paint	30-50
8	Dye ferromagnetic powder in slurry	40-80
9	Fluorescent ferromagnetic powder in slurry	50-100
10	Source of artificial white light (e.g. torch)	20-50
11	UV – A radiation source	5000-6700
12	Luxmeter	1800-2200
13	UV A radiation meter	2500-3400
14	Yoke defectoscope	4000-5500
15	Defectoscope provided with a coil	35000-44000
16	Reference specimen no. 1	1500-2400
17	Reference specimen no. 2	1600-2600
18	Static magnetic field intensity meter	2800-3400
19	Indicator of residual magnetic field intensity	1500-2000
20	Photographic camera	800-1000
	IN TOTAL	**56805-73920**

Table 4. Equipment for an X-ray laboratory and their costs

No.	Name of device or other equipment	Approximate cost (gross) 1 piece or set (PLN)
1	Wire brush, abrasive paper	50-100
2	Magnifying glass (magnification up to 4 times)	10-30
3	Universal slide caliper	30-100
4	Straightedge ruler (2 – 3 m)	5-10
5	Indelible markers	20-50
6	X-ray type radiographic image quality indicators (for steel, copper and aluminium)	500-600
7	Cassettes for films (rigid and elastic – 5 pieces)	150-250
8	X-ray films (of C3, C4 and C5 system – one package)	1200-1500
9	Lead shields for masking	50-200
10	Markers (lead or equivalent)	200-350
11	Radiogram optical density standard	350-600
12	Densitometer	3400-4200
13	Negatoscope	6000-11000
14	Automatic station for photochemical processing of films	35000-50000
15	X-ray apparatus	150000-175000
	IN TOTAL	**196965-243990**

The estimate of X-ray laboratory equipment does not include the cost related to the construction or adaptation of designated and separated rooms where ionising radiation will be used. Regulations concerned with this issue are presented in the law entitled Atomic Law. It should be noted that an X-ray laboratory should consist of at least an exposure room (where objects being tested are exposed to radiation), control room (where an operator adjusts exposure parameters and controls a process on real-time basis) and a dark room (where cassettes with films are prepared and where exposed films undergo photochemical processing). An X-ray laboratory should also have a room adapted for viewing radiograms; in such a room it should be possible to adjust white light (natural or artificial) intensity to an acceptable level. An estimated cost of building or adapting selected rooms for an X-ray laboratory, determined on the basis of the authors' own experience, amounts to approximately 1 million PLN. Therefore, the total cost of the organisation of radiographic tests should be estimated at between approximately 12 million PLN and approximately 1.25 million PLN. As regards radiographic testing of welded joints, the conclusion is that at the initial phase of creating an X-ray laboratory it is highly advisable to collaborate with another, possibly well-known, laboratory.

Ultrasonic Tests

Ultrasonic testing is another (in addition to radiographic testing) NDT method for examining welded joints. UT is rated among so-called volumetric methods [10, 11]. Ultrasonic tests are characterised by high mobility (due to the small size and light weight of the defectoscope) and high work safety. For this reason, in industrial practice, ultrasonic tests increasingly often replace radiographic tests. Equipment necessary for ultrasonic testing is listed in Table 5.

Table 5. Equipment for an ultrasonic testing laboratory and their costs

No.	Name of device or other equipment	Approximate cost (gross) 1 piece or set (PLN)
1	Wire brush	50-100
2	Magnifying glass (magnification up to 4 times)	10-30
3	Universal slide caliper	30-100
4	Straightedge ruler (2 – 3 m)	5-10
5	Indelible markers	20-50
6	Coupler	50-100
7	Angle grinder	300-500
8	Angle head (700, 450, 600)	900-1200
9	Straight head (2 MHz, 4MHz)	1100-1400
10	Double head (2 MHZ, 4 MHz)	1300-1900
11	Phased-array transducer	9500-11000
12	Ultrasonic defectoscope	24000-35000
13	Ultrasonic defectoscope for tests using TOFD and Phased-array methods	90000-110000
14	Scanner for tests using TOFD method	25000-30000
15	Standard no. 1	2500-2900
16	Standard no. 2	1700-2100
	IN TOTAL	**156465-196300**

As can be seen in Table 5, the total rounded-up cost of equipment for a UT laboratory is restricted within a range of approximately 160 thousand PLN to approximately 200 thousand PLN

Metallographic Tests and Hardness Tests

In many cases, metallographic tests and hardness tests supplement NDT methods [12, 13, 14]. For this reason, it was necessary to perform an additional analysis of equipment for such tests along with its cost. The analysis results are presented in Table 6.

As can be seen in Table 6, the total approximate cost of equipment for metallographic tests is restricted within a range of approximately 265 thousand PLN to approximately 355 thousand PLN. In relation to hardness tests, the cost is restricted within a range of approximately 95 thousand PLN to approximately 158 thousand PLN.

Summary

The initial stage of the study-related work involved the analysis of methods which should be offered by a renowned and fully professional

Table 6. Equipment for a metallographic and hardness testing laboratory and their costs

No.	Name of device or other equipment	Approximate cost (gross) 1 piece or set (PLN)
	Metallographic tests	
1	Magnifying glass (magnification up to 4 times)	10-30
2	Universal slide caliper	30-100
3	Straightedge ruler	5-10
4	Indelible markers	20-50
5	Band-saw for sampling	2200-4500
6	Precise cutter	15000-30000
7	Grinding–polishing machine for preparing metallographic specimens	29500-48000
8	Metallographic microscope	195000-240000
9	Etching reagents	100-200
10	Press for hot-mounting of test specimens	23900-32000
	IN TOTAL	**265765-354890**
	Hardness tests	
1	Wire brush	50-100
2	Magnifying glass (magnification up to 4 times)	10-30
3	Universal slide caliper	30-100
4	Straightedge ruler	5-10
5	Indelible markers	20-50
6	Angle grinder	300-500
7	Rockwell stationary hardness tester	33000-68000
8	Brinell stationary hardness tester	23000-35000
9	Vickers stationary hardness tester	31000-42000
10	Rockwell portable hardness tester	4000-4600
11	Brinell portable hardness tester	2400-3800
12	Vickers portable hardness tester	1900-3700
	IN TOTAL	**95715-157890**

NDT laboratory. Consulting NDT specialists and NDT companies revealed that a newly opened laboratory should be able to perform, at least, visual tests, penetrant tests, magnetic-particle tests, radiographic tests and ultrasonic tests. Visual tests should include endoscopic and videoscopic techniques. Penetrant testing should be based on dye and fluorescent testing techniques. Magnetic-particle tests should involve the use of wet dye and fluorescent magnetic-particle testing methods. Radiographic tests, due to testing sensitivity and expertise-based evaluation tasks, should be performed using X-ray lamps (X-radiation), i.e. X-ray radiography. Standard ultrasonic tests should involve the TOFD method. In turn, as regards destructive testing, a laboratory should be capable of conducting at least metallographic and hardness tests. Both methods usually supplement non-destructive tests, particularly when examining test joints made by welder-examinees or for purposes of welding procedure specifications. For this reason, metallographic tests and hardness tests were included in the activity scope of a planned laboratory, and the costs of such tests were subjected to analysis. The presented testing methods, selected mainly having tests of welded joints in view, directly determine the most important laboratory equipment. The means necessary for implementing individual testing methods, along with their numbers and costs are presented in Tables 1-6. In turn, the approximate and rounded off cost of this equipment is presented in Table 7 and in Figure 9.

As can be seen in Table 7 and Figure 9, the total cost of laboratory equipment is significant and amounts to between 875 thousand PLN and 1.255 million PLN. The highest cost is that of equipment for metallographic tests, whereas the lowest is that for classical penetrant tests. High equipment costs are also characteristic of equipment for radiographic and ultrasonic testing. As regards visual tests, the cost of equipment depends largely on the use of highly advanced techniques such as endoscopy and videoscopy. Standard visual tests do not entail high investment costs. In comparison with other testing methods, equipment costs related to magnetic-particle tests and hardness tests can be regarded as medium.

The costs presented above indicate that the organisation of a new laboratory capable of successfully competing in the NDT services market is very difficult as requires huge costs. In many cases, organising a fully-equipped laboratory is practically impossible. An alternative solution could be organising a laboratory in stages. In the first place, it would be necessary to start with services requiring relatively low investments (e.g. standard visual or penetrant tests). As profit grows it would be advisable to invest in more advanced, thus more expensive testing methods. As can be seen, apart from

Table 7. Approximate cost of laboratory equipment

No.	Testing method	Method designation	Approximate equipment cost (PLN)
1	Visual tests	VT	89000 – 205000
2	Penetrant tests	PT	14000 – 19000
3	Magnetic-particle tests	MT	56000 – 74000
4	Radiographic tests	RT	196000 – 244000
5	Ultrasonic tests	UT	160000 – 200000
6	Metallographic tests	-	265000 – 355000
7	Hardness tests	-	95000 - 158000
		IN TOTAL	**875000 - 1255000**

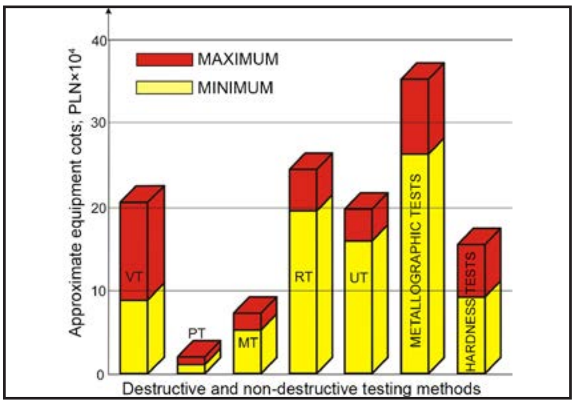

Fig. 9. Approximate costs of destructive and non-destructive laboratory equipment

specific cases, spreading investments in time would significantly facilitate the organisation of a laboratory. It should be also noted that the above laboratory-related costs include equipment but do not contain the cost of adapting (or building) rooms housing a laboratory. Due to health and safety at work as well as environmental protection, such costs could be high.

The problems presented do not exhaust the issues related to NDT equipment. As possible equipment configurations are many and varied, their costs may differ significantly. However, as was the authors' intention, this study should help to optimise a financial policy related to professional NDT laboratory organisation.

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