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IO3 - Kit of Education Materials for EDTT Training Course

Public version - for Trainees

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Contents

I. Introduction to the kit

This IO3 is concerned with the development of the necessary resources for the future implementation of the EDTT qualification at national level, and it targets both trainers/teachers as well as trainees and the ANB's (EWF's Authorised Nominated Body) to facilitate the learning process, and the transferability of the qualification.

It includes the development of a Handbook with training tools and innovative assessment tools (restricted access to the EWF's national ANB's), such as Problem-Based Learning assignments, as well as practical exercises for the classroom. The contents of this Handbook (i.e. the kit of EDTT educational materials) will be piloted on National Pilot Events with the TRUST target groups, to account for any improvements deemed necessary.

All partners have contributed for the development of the educational materials and were involved in the elaboration of all assessment tools to be used in the Training Course. TRUST partners will ensure that the exercises and assessment tools created are fully aligned with Destructive Testing field by developing real case studies and Problem-Based Learning assignments based on real industrial contexts. This will ensure trainees enrolled in the EDTT training course, to have the opportunity to solve issues that professionals working on Destructive Testing face on a daily basis, hence better preparing them to address some of those issues in real life.

Even though the developed assessment tools have restricted access to EWF's National ANB's, they will be translated to be available to partners' national languages (PT, IT, PL and RO), as well as the practical exercises for the classroom, ensuring their correct application at national level when implementing the EDTT training course. This is in line with the harmonized characteristics of the EDTT Qualification, which means that all trainees have access to the same training, the same exercises, and the same assessment procedures, regardless of their contexts.

II. Handbook

For confidentiality reasons, this is the only part of the Kit of Educational Materials that trainees can access. These materials are addressed to support trainers delivering the technical contents of the EDTT training course, to create a dynamic learning environment based on a learner-centered approach. At the same time trainees can use it as a guide for further studying of the topics.

It is structured following the exact same structure of the 3 competence units that are part of the EDTT Curriculum (developed under IO2):

1. Introduction to Destructive Testing
2. Mechanical Tests (Tensile Tests, Bend Test, Charpy Impact Strength Test, Fracture test, Hardness Test)
3. Measurement uncertainty

1. Introduction to Destructive Testing

1.1. Introduction to Destructive Testing and Safety Rules in Destructive Testing

In the modern world we use many different materials to build structures, components, and machinery. Proper design of these items requires good knowledge of their constituent materials properties namely mechanical properties such as tensile strength, stiffness, toughness, hardness, and ductility.

Different types of tests have been proposed to determine these properties, generally called mechanical tests or destructive tests, as they usually require the destruction of the piece being tested. As such, these tests are normally used by sampling and could serve several purposes namely:

- Determine material properties required for the design of components and structures.
- Reception of raw materials to confirm their properties' compliance with the specification.
- Qualification of some manufacturing or joining processes. Welding is a typical and extremely important example.
- Quality of production welding joints.
- Investigation of accidents or failure cases.
- Research for development of new materials or new manufacturing processes.

Over the last century, hundreds of different mechanical tests have been proposed to determine or analyse different properties, section two will introduce several tests often used to determine basic material properties and with particular relevance in welding. To better understand these tests, we

shall introduce below some basic concepts concerning testing and materials behaviour, particularly of metallic materials, and welding joints.

1.1.1. Basic Concepts

The mechanical strength of a given material is an important characteristic. However, expressing this as the maximum load that the material can withstand without failure is not practical because a thicker piece of material will support a higher load. Another important property or parameter in mechanical testing is the elongation of a given length of material at a given load. Like with the load using the elongation of the material is not practical because a longer piece of material will have a higher elongation. Thus, in mechanical testing and engineering we use the concepts of mechanical stress and strain to quantify these material properties.

Stress is defined as the load applied to the piece of material divided by the resisting cross of the piece This is usually named direct stress or normal stress because the cross section is perpendicular to the force and represented by the Greek letter sigma (σ). In Figure 1.a) if F=20 kN and the cross-section AA´ is 100 mm^2 then:

F=20 000N

AA'=10 mm^2=0.0001 m^2 and the stress:

$$\sigma = \frac{20\,000}{0.0001} = 200000000\ {}^{N}/_{m} = 200000000\ Pa = 200\ MPa$$

So, the mechanical stress has the same units as pressure, Pascal (Pa) or more often in materials behaviour and mechanical testing multiples of this like kilopascal (kPa) or megapascal (MPa).

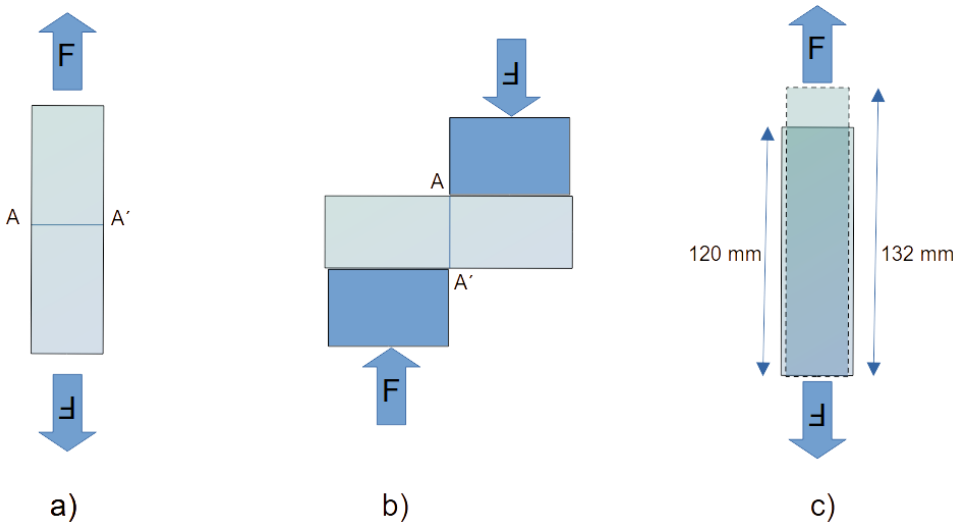


Figure 1 - Schematic representation of stresses and strains on a bar of material

We can also have a different type of stress where the resisting cross section is parallel to the force as exemplified in Figure 1b), this is termed shear stress and represented by the Greek letter tau (τ). In Figure 1b) if the bar has the same cross-section of 100m2 and the force is also 20 kN then the shear stress in section AA' will also be 200 MPa.

Strain is defined as the elongation of the piece (increase or decrease of length) divided by the piece original length, often expressed as a percentage, and represented by the Greek letter epsilon (ε). In the example of Figure 1c), if the initial length of the bar is 120 mm=0.12 m and the final length under a tensile force F is 132 mm=0.132 m then the strain is:

$$\frac{0.132 - 0.120}{0.120} = 0.1\,{}^{m}/_{m}$$

Or multiplying by 100 to convert into a percentage 0.1x100%=10%

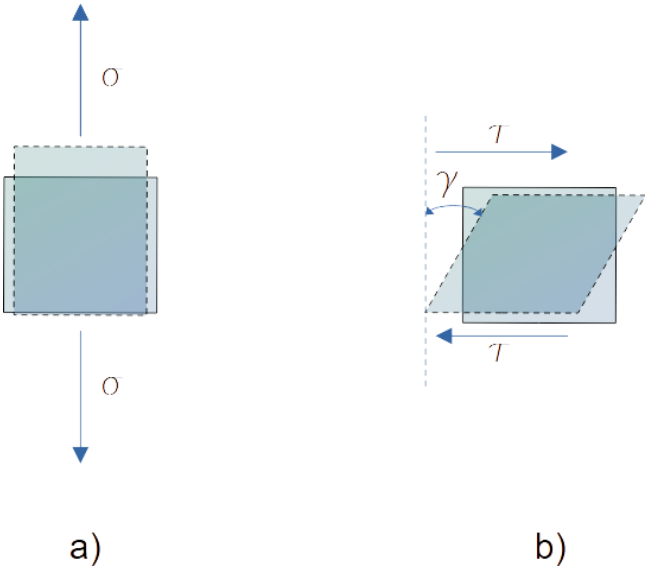


Figure 2 - Schematic representation of direct and shear strains

Likewise shear stresses will also cause a strain, usually denoted by the Greek letter gamma (γ), although this strain is more difficult to visualize. Whereas normal stresses cause only a stretching of a particular shape, shear stresses cause a distortion of the original shape like exemplified in Figure 2b), where a square becomes a rhombus. Physically the shear strain is the angle of distortion shown in Figure 2b).

It is common experience that some materials, like rubber for instance, can be stretched to a longer length by applying a force but when released the material recover its original length, whereas other materials, a copper wire for instance, when bent or stretched will keep the deformed shape/length after being released. The former behaviour is called elastic deformation/strain whereas the latter is termed plastic deformation/strain. In fact, most materials, and namely metallic alloys, exhibit both behaviours. They are elastic up to some stress level and become plastic thereafter and up to the stress at which they fracture. The stress at which the behaviour changes from elastic to plastic is named yield stress and the stress at which failure occurs fracture stress or tensile strength. The knowledge of this stresses is very important for a reliable use of materials and technological processes such as welding. The tensile test that will be introduced in detail in Section 2 allow us to precisely determine these important properties.

Materials that exhibit the behaviour above, with considerable plastic deformation before failure, are termed ductile materials. There are other materials, classical examples are ceramics and glasses, that fracture when they are still in elastic regime or at very little plastic deformation, these are called brittle materials. Brittle does not mean necessarily “weaker” in the common sense of the word, in fact many

high strength materials like tool steels or high-speed steels (often used to make tools to cut or machine other materials) show this behaviour. The main difference is in the energy required (or absorbed) to fracture the material. As the elastic deformation is very small compared with the plastic one, the energy absorb in the fracture of brittle materials is also small despite their higher fracture stress. Although having a lower fracture stress ductile materials will absorb more energy to fracture due to there much larger plastic deformation.

This led us to another concept, or mechanical property, called toughness. A high toughness material is a material that absorbs a high value of energy to fracture. This does not mean that high toughness materials are better than low toughness ones, it depends on the application we want to use them for. If we hammer a piece of construction steel it will bend and dent but will not break, on the other hand if we do the same to a drill bit, made of high strength steel, it might break easily or even shatter in several pieces. A drill bit in construction steel would wear off and loose its cutting edges very fast whereas a bridge made of high strength steel, besides the very high cost, would be very sensitive to impacts and defects that might develop in service, and could collapse without any previous warning.

The material toughness can be derived from a tensile test, but this is not common. Because this property is very important, especially in construction materials, specific tests have been proposed to determine it. The most widely used is the Charpy V impact test in which a notched specimen is broken by an impact. By carefully extracting the test piece we can position the notch in a particular region of our material, to probe a specific location and not all volume of it. A good example is a welding joint Figure 3, in a welding joint we can distinguish at least three regions:

- Base metal – material far away from the weld and not affected by the heat cycle of the weld.
- Weld metal – material that was melted and solidified again to join both parts.
- Heat affected zone (HAZ) – region adjacent to the weld metal that, despite not melted, was submitted to very high temperatures, and suffer structural modification due to that.

The last region is usually the most problematic because the heat sink effect of the rest of the component can cause high cooling rates on this region of the weld and consequently the formation of hard structure or phases. As mentioned before hard phases are usually brittle which might compromise the mechanical strength of the weld joint. The Impact test is very useful, and therefore, very often used to control the properties of the HAZ and make sure that the welding procedure (or the welder) are not causing this problem. Figure 3 also shows, schematically, the positioning of an impact test specimen to probe the properties of the HAZ. As the notch is positioned in this region, we are determining the properties of the HAZ and not those of all the welded joint.

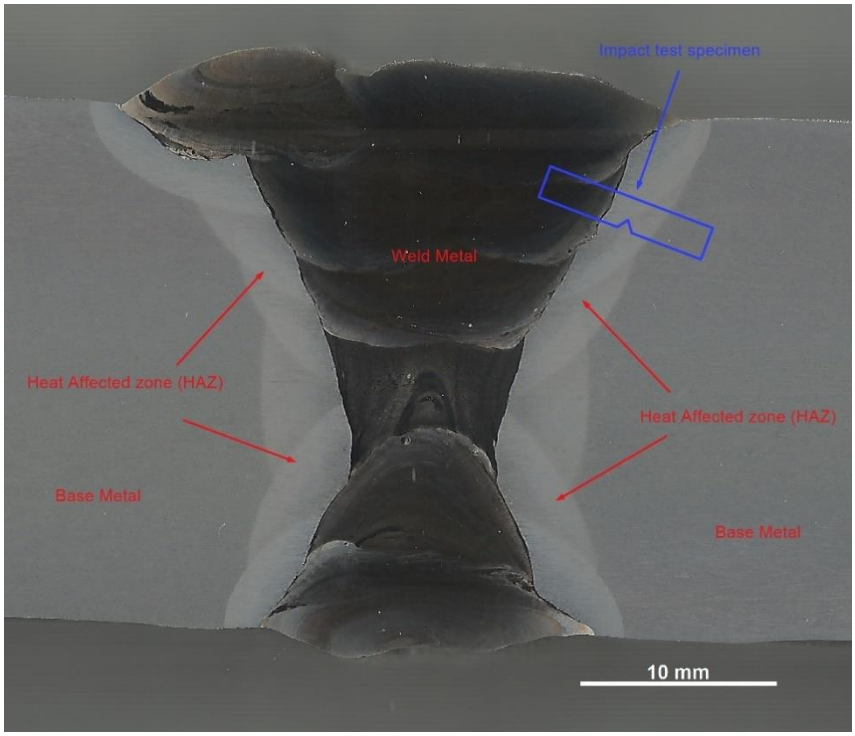


Figure 3 - Macrography of a weld joint showing the different regions a possible location of an impact specimen to test the HAZ.

The last concept or property concerning mechanical properties and testing is hardness. This is a very important property both by itself but also because of its relationship with other material properties. In our day life experience, we are familiar with the concept of hardness, instinctively one has the notion that, for instance, rubber is softer than metal or glass. However, to use this in engineering we need a more quantitative way to define and measure this property. The first attempt was the Mohs scale proposed for studying minerals. This scale consists of ten minerals starting with talc (the softer) and with increasing hardness up to diamond (the hardest). If some material is scratched by one of the minerals is softer than that mineral if not is harder. Although still used in mineralogy, this scale is not very useful in evaluating hardness of modern engineering materials. It only has ten hardness grades and the difference between these grades is not constant, so the discrimination we can get between different materials is very small. Modern techniques to measure a material hardness are based on what we call indentation hardness. In these techniques a punch with a hard tip of some standard geometry is pressed against the surface of the material being tested with some standard load and for a certain time. The hardness is evaluated by the size of the marking left on the surface, or by the depth that the punch penetrates into the material. According to this, hardness can be defined has the material resistance to plastic deformation. As with the impact tests, hardness tests, besides testing materials in general, are much used in welding because they are also very localized, the width of the mark is less, or often much less, than a millimetre, thus, they can probe particular material regions in the

weld joint, Figure 4 shows hardness indentations in the different regions of a welded joint. Since hardness is related with the material capability to deform plastically is not independent of other material properties that we have discussed before. Thus, as a rule of thumbs, a hard material will be brittle, and show high strength and low toughness and conversely a softer material will be ductile and exhibit low strength and high toughness.

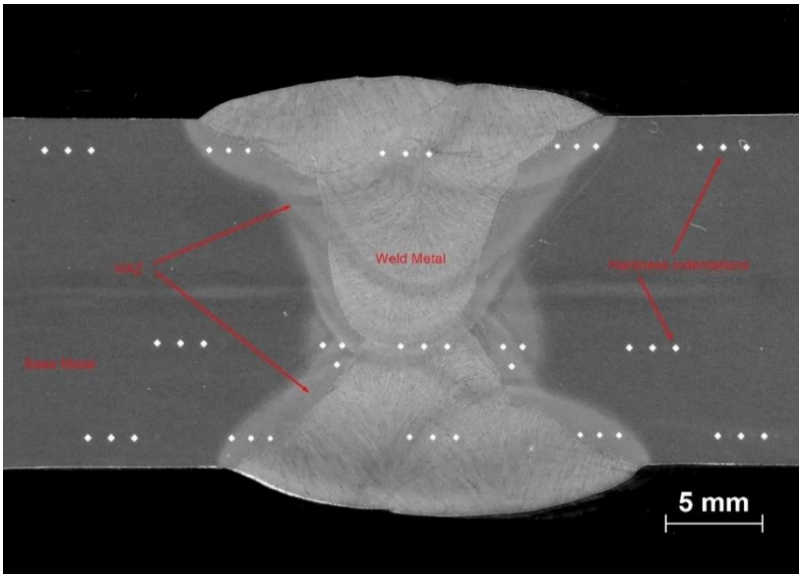


Figure 4 - Hardness indentations in a weld joint.

1.1.2. Safety Issues

Mechanical tests are not, in general, particularly dangerous, nevertheless, has with most laboratory work severe injuries and damage might happen if the required test operations are not carried out according with proper procedures and due care.

Risks and safety issues regarding mechanical testing can be broadly divided into three classes, test equipment, operator, environment. These different aspects are not independent of each other and are often interrelated.

- Test equipment safety – A proper operation of the test equipment's is a fundamental requirement to guarantee the safety of the testing laboratory. Thus, the operator must have proper training on the operation of the equipment's, their working principles and design (we shall develop this matter in more detail in Section 1.2). Improper operation of the test equipment can also cause damage to the test specimens themselves with consequent low quality and reliability of the tests results obtained. All equipment should be installed and checked accord-

ing to manufacturer instructions and with, for instance, appropriate electrical supply, ventilation, and space to be safely operated. The laboratory must also have adequate procedures for maintenance and verification of the testing equipment. Improper installation/operation of equipment might potentiate all other risks.

- Operator safety – operators often need to manipulate heavy parts to perform the equipment configuration, such as heavy test pieces and/or test jigs, the use of appropriate protection footwear should be highly recommended or even mandatory. Likewise, the use of mechanical protection gloves is also highly recommended, many test pieces might have sharp edges or residual splinters from the machining operations which might cause cuts and bruises. Nevertheless, during the test setup is often needed to make some measurements using callipers or verniers which may be difficult to perform with heavy gloves, thus, thinner gloves like latex ones should also be available. Some tests, particularly tests on brittle materials or composites, might shatter in several pieces or project microfibers, the use of some eye or facial protection is also highly recommended. This kind of protection might also be required when performing impact tests at temperatures below ambient. These temperatures are usually achieved with cryogenic baths or liquid nitrogen which might spill causing burns or eye damage. Dangerous or aggressive chemicals are not common in a mechanical test laboratory, but some acid-based solutions might be required at times, as well as degreasing products which might be irritating in contact with the skin. Latex gloves or similar should also be available when needed.
- Environment safety – As mentioned previously a mechanical testing laboratory will not work, in general, with particularly dangerous materials. Nevertheless, some chemicals might have to be handled and specially, in case the laboratory operates hydraulic equipment, some large amounts of hydraulic oil might have to be periodically disposed of. These substances can represent potential hazards for both laboratory personnel and the environment. The staff should have proper training on how to handle and store these materials, whereas the laboratory should have appropriate procedures to dispose of those substances, usually by contracting a specialized company to recycle or properly destroy them.

1.2. Design of Destructive Testing Machinery and Equipment

To perform a mechanical or destructive test we always need an equipment with a moving part to apply the loads required and a fixed part to support or hold the test piece. The latter must, of course, be able to resist the applied loads without appreciable deformation. We shall discuss below the major design principles and characteristics of three types of equipment which are representative of most situations concerning mechanical test:

- Tensile machines - tensile load applied progressively up to failure.
- Impact machines - load applied instantly by an impact.
- Hardness machines - compression load applied progressively.

Tensile test machines are probably the most used mechanical test equipment, despite the name they can also be used for many other types of mechanical tests, in fact they are sometimes called universal testing machines. These machines can be broadly divided in two types electromechanical, in which the force is applied by an electric motor, and servo-hydraulic, in which the force is generated by a hydraulic jack or actuator. Despite differences inherent to the specific driving method of each type of machine the basic design is similar. We need to have a load frame to enable force to be applied to the specimen, some means to grip the specimen into the load frame and sensors to acquire the test data that we need.

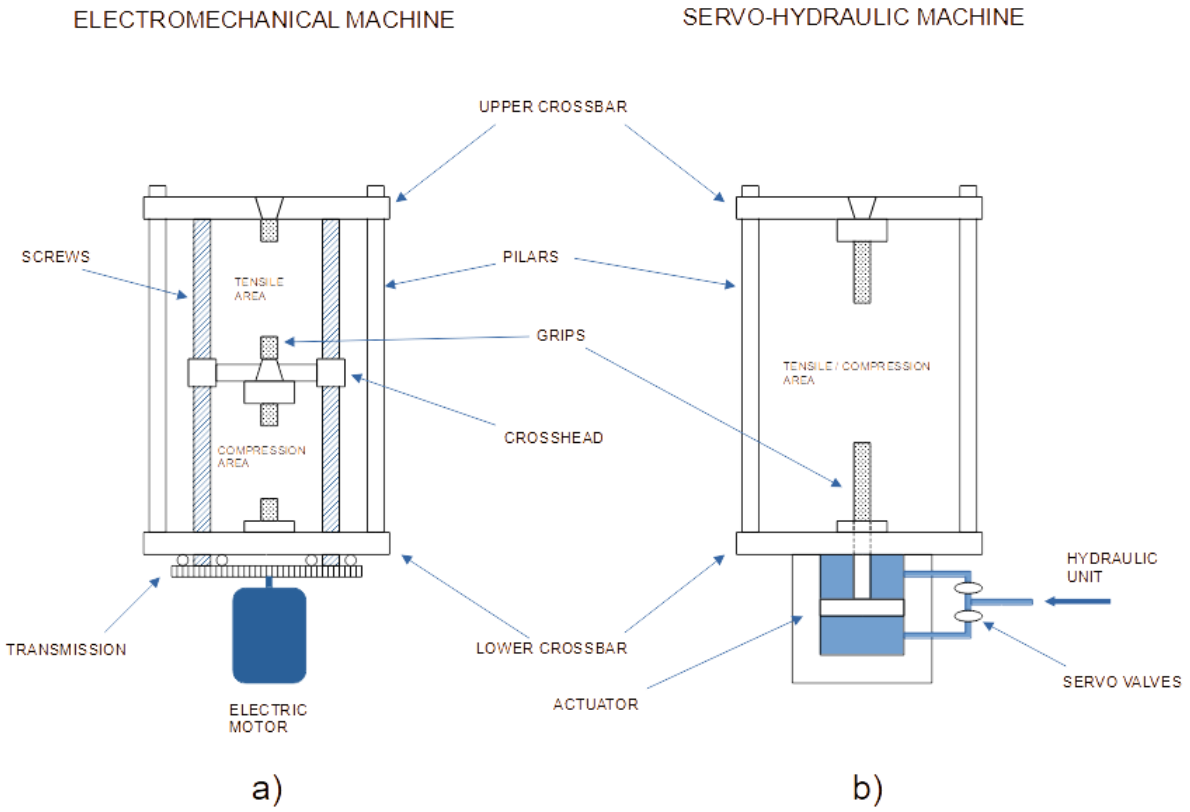
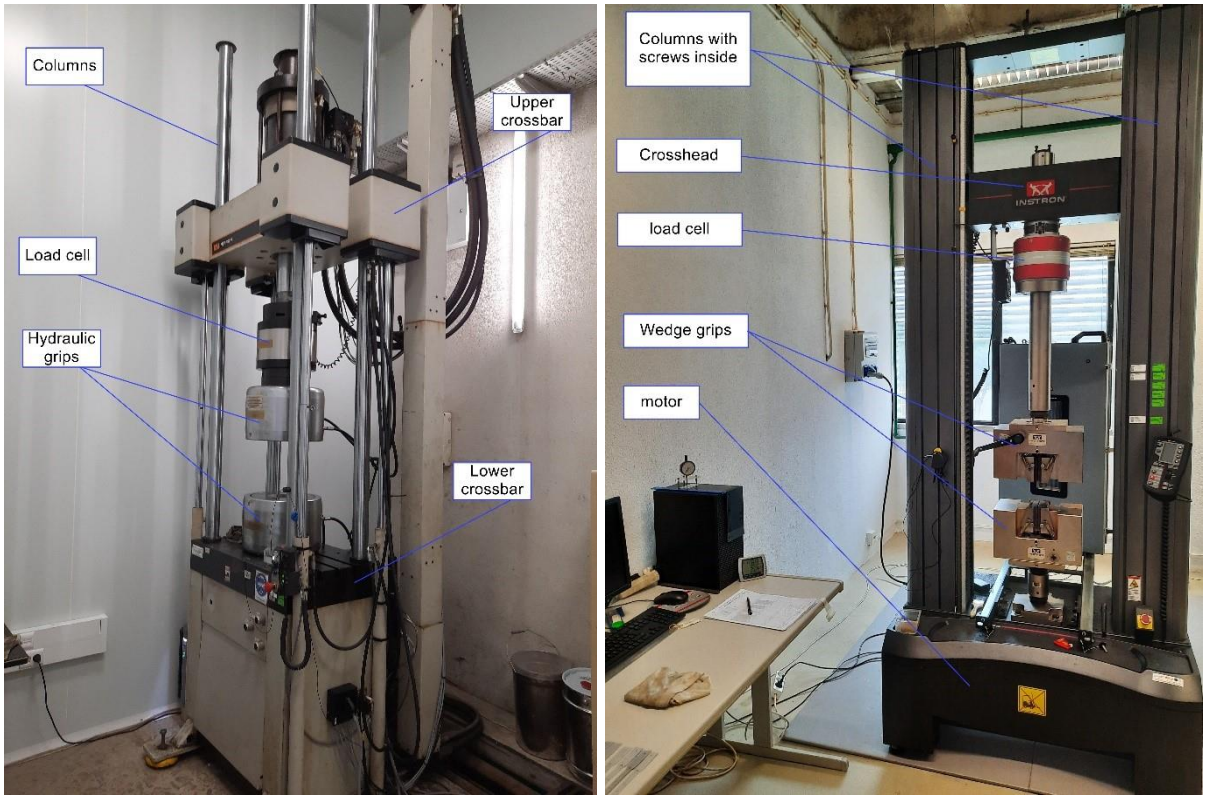


Figure 5 - Schematic representation of tensile testing machines main designs.

Electromechanical machines consist basically of two vertical steel columns, parallel to each other and connected at top and bottom sides by rigid and static cross bars, Figure 5a) (some large capacity machines might have a horizontal configuration but this is not common). Parallel to the vertical bars there are two threaded bars, or screws, that can rotate driven by an electrical motor usually located below the machine load frame. These screws can drive the movement of a mobile cross bar, usually called crosshead. This machine configuration can have a single testing area in which the test specimen is gripped between the crosshead and one of the cross bars, or two testing areas one below the crosshead, usually for compression, bending and similar tests involving compression loads, and another testing area above the crosshead specifically for tensile tests. This is the configuration depicted in Figure 5a), whereas in Figure 6b) is shown a single testing area machine.



a) *b)*

Figure 6 - Mechanical test machines; a) hydraulic four column type fitted also with grips hydraulic; b) electromechanical fitted with manual wedge type grips.

Hydraulic testing machines have a load frame similar to the electromechanical equipment, but they have a hydraulic actuator either on the top or bottom cross bar to apply the load, Figure 5b). Unlike the EM machines were the two-column configuration is more common, hydraulic machines, especially large capacity ones, often have four columns, Figure 6a). Although older designs of this type of machines might also had two testing areas in modern times the single test area configuration is more common, Figure 5a) and Figure 6a).

To perform tests the testing machines must have in their design some other parts or accessories which are common to all machines regardless of the type of driving system. All machine designs must incorporate a system to grip the specimen in the machine, and this system must be robust enough to support the required test loads. As mechanical tests are based on the application of load to the specimen, the machine design must also include a sensor to measure the load being applied during the test. Several systems have been used in the past but in modern designs this sensor is a load cell integrated in the machine load train.

Figure 7 shows schematically some of the most common gripping designs. These are usually hydraulic Figure 8b) or mechanical systems Figure 8a). The former is more flexible since the gripping force can be adjusted to the particular test being performed. The mechanical ones consist of two serrated wedges (they are sometimes referred to as wedge grips) that slide over an inclined fixed surface. Providing there is no slippage of the specimen then the gripping force increases with the tensile loading.

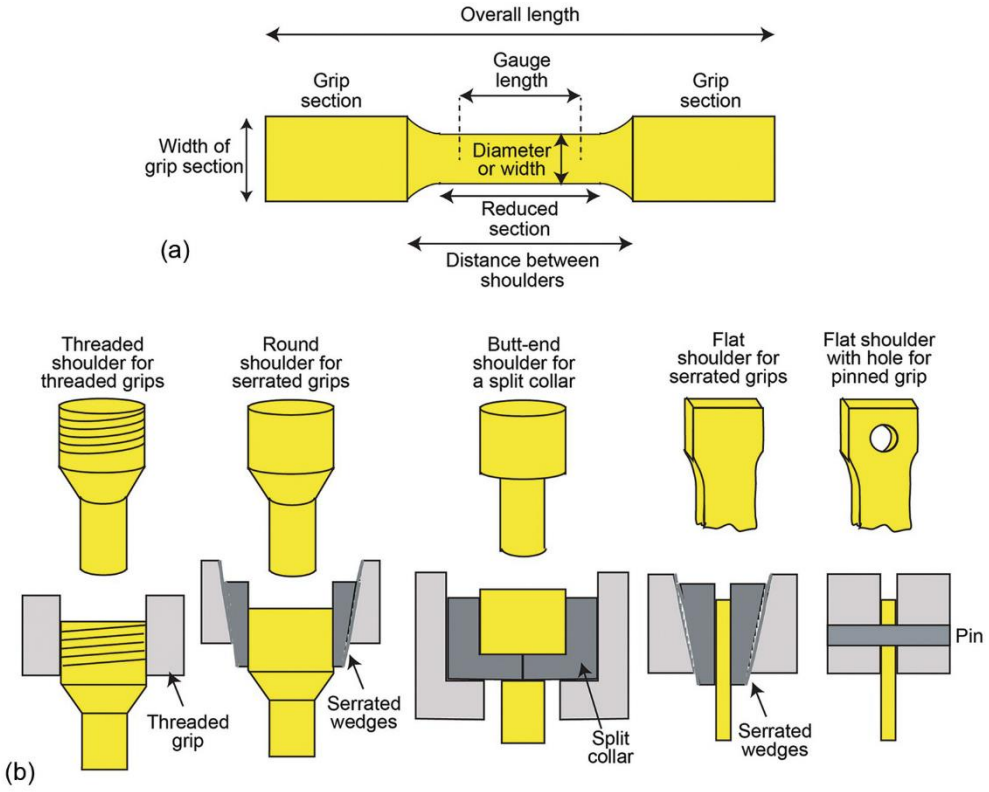
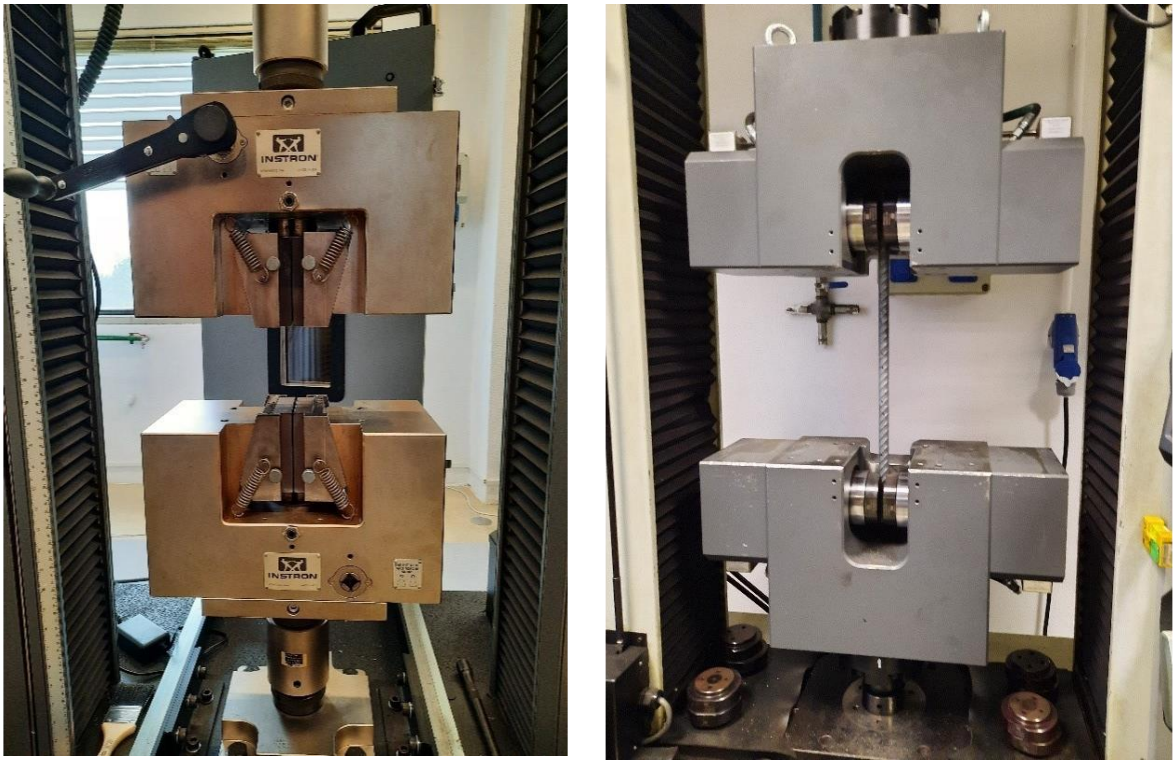


Figure 7 - Different methods of specimen grips.
https://static.cambridge.org/binary/version/id/urn:cambridge.org:id:binary:20210415111914621-0122:9781108943369:83789fig5_1.png?pub-status=live; consulted in 15-03-23



a) *b)*

Figure 8 - Two examples of mechanical test machine grips; a) mechanical wedge type; b) hydraulic.

Finally, all modern machine designs incorporate a load transducer to monitor the loads applied to the specimen during the test. Different types of transducers have been used in the past but modern designs rely on a load cell within the machine load train, attached to either the fixed cross bar or the moving crosshead/piston, Figure 6. Modern testing machines also include a displacement transducer connected to the crosshead or hydraulic piston to monitor their position and movement during the setup and the test itself.

To carry out many mechanical tests (and particularly tensile tests) the machine displacement sensor is not accurate enough as it also measures the deformation of the machine itself. Although not part of the machine design one additional transducer is required to perform accurate tests. This is an extensometer, which allow us to measure the actual deformation or strain of the test specimen itself. In modern times there are several types available including contactless laser and video image correlation, but the most common is a mechanical system consisting of two arms with knife edges, attached to the specimen body with clips, springs or even elastic strings. Figure 9 shows examples of these mechanical extensometers, one of them attached to a rebar specimen during a test.

a) b)

Figure 9 - Two examples of mechanical contact extensometers. In b) the extensometer is attached to a rebar with elastic strings during a test.

Impact tests are usually performed in machines that rely on gravity to apply the impact on the test specimen. The most common design is the pendular configuration initially proposed at the beginning of XX century and still used now a days. This design consists of a very heavy base (usually a concrete slab and heavy steel plates). Vertical pillars are installed on this base to support a swinging arm with a heavy hammer in the end. The specimen is supported by an anvil on the bottom of the machine, in the path of the hammer and in a position that the notch is aligned with the hammer striking edge. When the pendulum is released without any specimen in the machine it will swing all the way to the other side and raise to the same height from which it was released; if now a specimen is in the machine the movement of the pendulum will be retarded when striking the specimen and raise to a lower height. The difference in potential energy corresponding to the difference of height is the energy absorbed to fracture the specimen. Figure 10 shows schematically the working principle of this machine. This design has remained largely unchanged since the impact test was first proposed. Major developments concerned the operation mode and the energy reading. Older models were manually operated using an auxiliary arm operated by a crankshaft to raise the pendulum to its launch height and the reading of energy was by a dial with two needles, one rotating together with the pendulum which dragged the other; when the pendulum reaches its maximum height after the impact and falls back the dragged needle remains on the maximum position indicating the energy. Modern machines are

usually computer controlled with fully automatic positioning arms a digital energy reading. Figure 11 shows both an old model and a modern one.

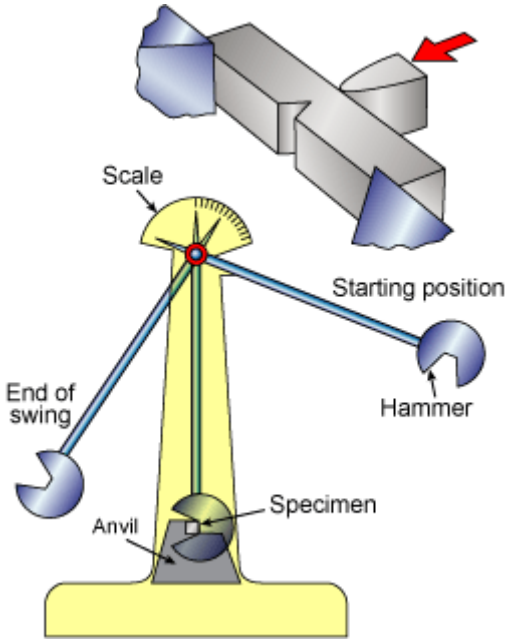
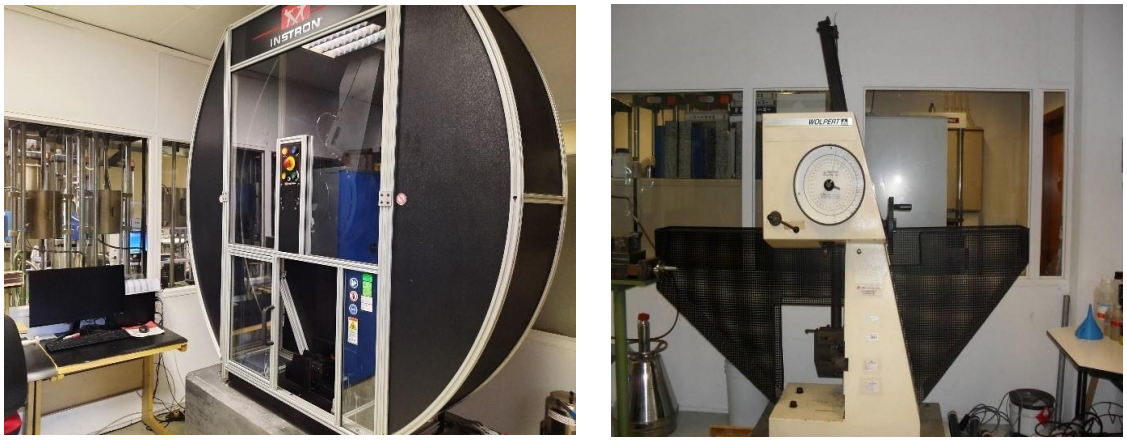


Figure 10 - Schematic representation of an impact test pendulum and a specimen in the test position.
https://www.twi-global.com/images/00022/9757.gif; consulted in 28-03-2023



a) *b)*

Figure 11 - Examples of impact test pendulums; a) modern computerised equipment, fully enclosed for safety; b) older manual equipment with only partial protection.

Has with the impact test modern hardness test techniques start being developed in late XIX early XX century, and the basic machine design remain broadly unchanged up to present times. Major devel-

opments being made in the test control and measurement which are often fully automatic and computerized nowadays, although, manual continue to be used often. The main features of this type of equipment are a solid and stiff platform to support the specimen being tested (this platform has usually a lifting system like a screw to adjust the heigh to the size of the specimen); a punch with some geometry (like a sphere, a cone or a pyramid); a loading system to press the punch against the specimen surface and a small microscope that can be interchanged with the punch and allows to choose the right spot prior to the test and to measure the size of the indentation left on the surface after the test. Among the several techniques used nowadays to measure the hardness, one relies on the depth that the punch penetrates the material surface and not the size of the mark left on it, but the remaining principles still apply, and it is common that one machine can perform several of these techniques. Figure 10 shows a schematic of hardness test machine, whereas Figure 13 shows both a fully manual model and a modern fully automatic one.

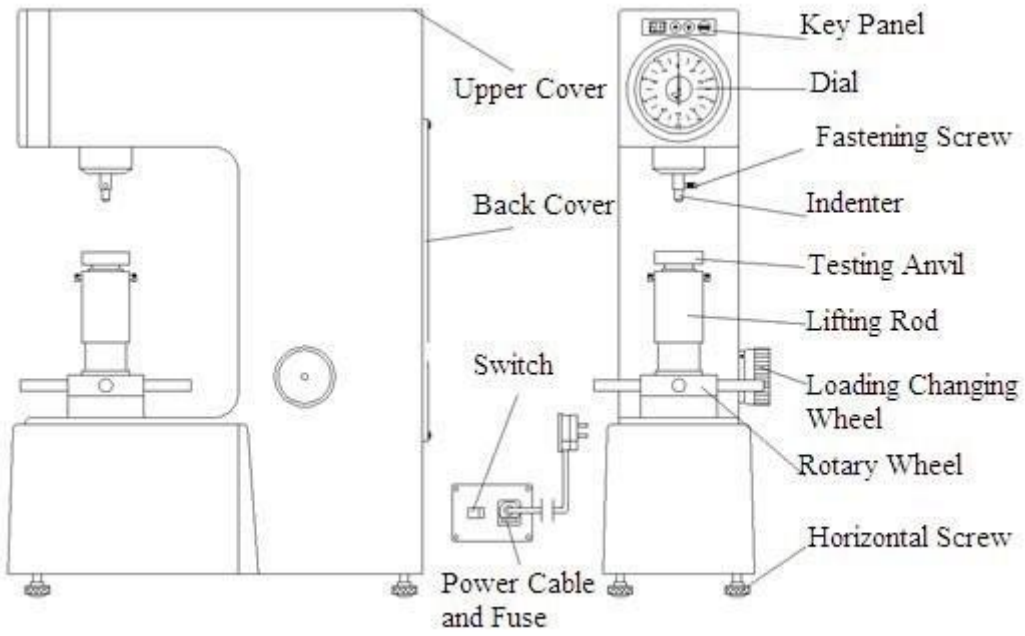
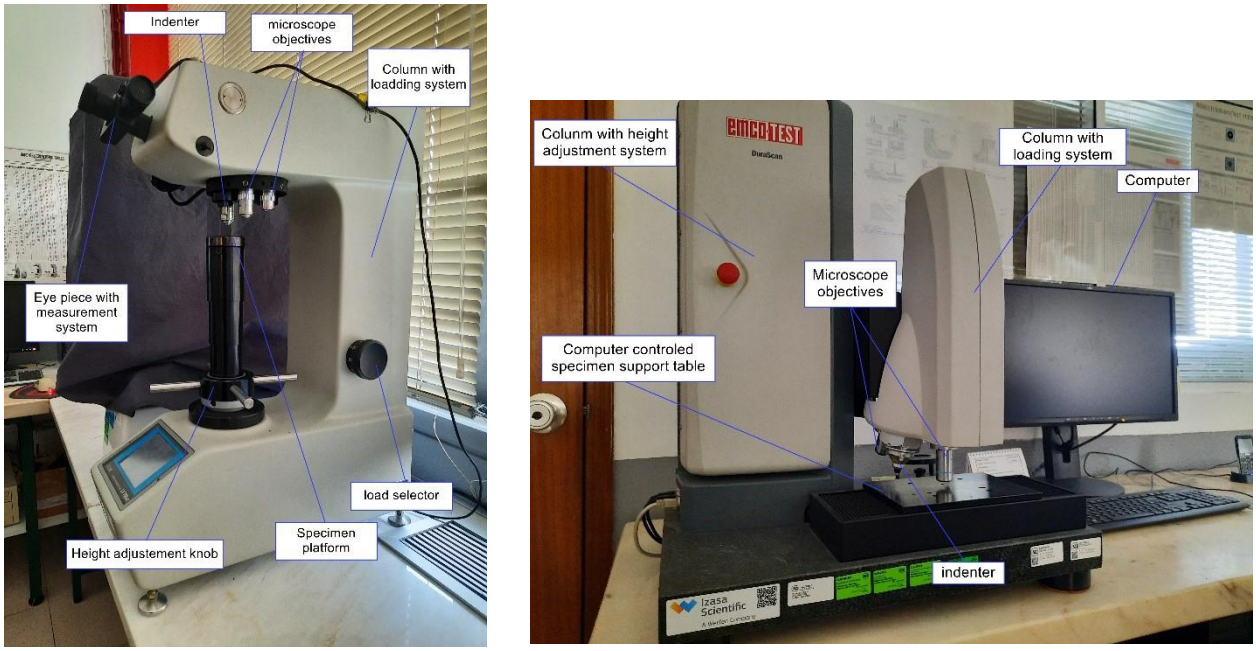


Figure 12 - Schematic representation of a hardness test machine (durometer).
https://www.researchgate.net/figure/Schematic-diagram-of-Vickers-Hardness-Test-7_fig5_338430669; consulted in 20-03-23



a) *b)*

Figure 13 - Examples of durometers a) manually operated equipment; and b) fully automatic equipment (computerised).

2. Mechanical Tests (Tensile Tests, Bend Test, Charpy Impact Strength Test, Fracture test, Hardness Test)

2.1. Tensile Tests of Metals at Room Temperature

2.1.1.1. Introduction

The tensile test is the basic type of test for metals with engineering applications and allows the basic properties of the materials to be determined. The test involves axial stretching of specimens of a specific shape in the grips of a testing machine. The specimens used for the test can be divided into a tensile part and a gripping part. In the specimens used for this test, there is a measuring section for tensile testing and a gripping section for gripping and load transfer. grips and for load transfer. Generally, cylindrical or flat specimens are used for tensile testing.

The tensile test is carried out by moving one of the jaws at a constant speed or a constant rate of load build-up. During the test, the dependence of the increase in gauge length on the tensile force is recorded, and at the end of the tensile test the strength properties are determined. The shape of the resulting graph depends on the type and condition of the material being tested. For low-carbon steels and metals with high ductility, graphs with a pronounced yield point are generally obtained, while for high-strength materials without a pronounced yield point. From the moment the load is applied, the elongation of the specimen increases in direct proportion to the loading force until the so-called yield point (elastic limit) is reached. After exceeding the proportional limit, a clear increase in specimen elongation is observed at constant or fluctuating of the specimen is observed at a constant or fluctuating level of the loading force. This corresponds to the yield strength yield strength Re. With a further increase in elongation, there is an increase in force, but no longer in a proportional to the elastic deformation range. When the maximum force - Fm - is reached, a local constriction of the specimen develops, called a neck. This is the cause of the slow decrease in force. At the end of the test, the specimen breaks. After the specimen breaks, the length of the gauge length and the dimensions of the local necking.

2.1.1.2. Description of the tensile test procedure

The purpose of the procedure is to ensure that the tensile testing of metals is carried out correctly. The procedure specifies the method for tensile testing of metallic materials and defines the mechanical properties which can be determined at room temperature.

The procedure has been written based on EN ISO 6892-1 standard.

2.1.1.2.1. Principle

The test consists of straining the test specimen using a tensile force, usually to fracture, to determine mechanical properties such as:

- **Percentage elongation after fracture – A**

  Permanent elongation of the gauge length after fracture expressed as a percentage of the original gauge length

$$A = \frac{L_u - L_0}{L_0} \cdot 100\% \qquad (1)$$

  where

  L_u – final gauge length after fractur,

  L_0 – original gauge length.

  For the manual determination of the elongation after fracture A, each end of the original gauge length L_0, shall be marked by means of the fine marks, scribed lines or punch marks, but not by marks which could result in premature fracture. The original gauge length shall be marked to an accuracy of ±1 %.

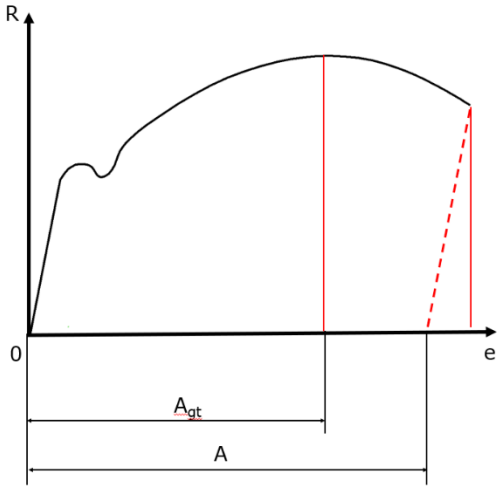
  For proportional test pieces, the calculated value of the original gauge length may be rounded to the nearest multiple of 5 mm, provided than the difference between the calculated and marked gauge length is less than 10 % of L_0.

  If the parallel length L_c, is much greater than the original gauge length, as for instance with unmachined test pieces a series of overlapping gauge lengths may be marked.

  In some cases, it can be helpful to draw a line parallel to the longitudinal axis, along which the gauge lengths are marked.

- **Percentage total extension at maximum force - A_{gt}**

  Total extension (elastic plus plastic extension) at maximum force, expressed as a percentage of the extensometer gauge length L_e (initial gauge length of the extensometer used for measurement of the extension).



e – percentage extension – strain, expressed as a percentage of extensometer gauge length,

R – stress,

A_{gt} – Percentage total extension at maximum force,

A - •Percentage elongation after fracture

Figure 14: Examples of extension [1].

- **Percentage reduction of area – Z**

Maximum change in cross section area which has occurred during the test, expressed as a percentage of the original cross section area.

$$Z = \frac{Z_0 - Z_u}{Z_0} \cdot 100\%$$

where

S_u – minimum cross-sectional area after fracture,

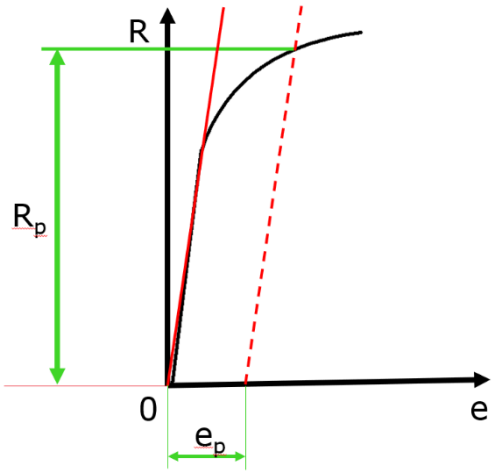
S_0 – original cross-sectional area of the parallel length.

- **Proof strength, plastic extension, R_p**

Stress at which the plastic extension is equal to a specified percentage of the extensometer gauge length.

A suffix is added to the subscript to indicate the prescribed percentage, e.g. $R_{p0,2}$

For the determination of Rp, the use of extensometer is mandatory



e – percentage extension – strain, expressed as a percentage of extensometer gauge length,

e_p – specified percentage plastic extension,

R – stress,

R_p – proof strength, plastic extension

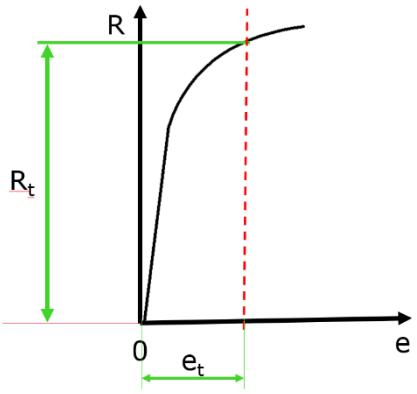
Figure 15: Proof strength, plastic extension, Rp [1].

- **Proof strength, total extension, R_t**

  Stress at which total extension (elastic extension plus plastic extension) is equal to a specified percentage of the extensometer gauge length L_e.

  A suffix is added to the subscript to indicate the prescribed percentage, e.g. $R_{t0,5}$

  For the determination of R_t, the use of extensometer is mandatory



e – percentage extension,

e_t – percentage total extension,

R – stress,

R_p – proof strength, total extension

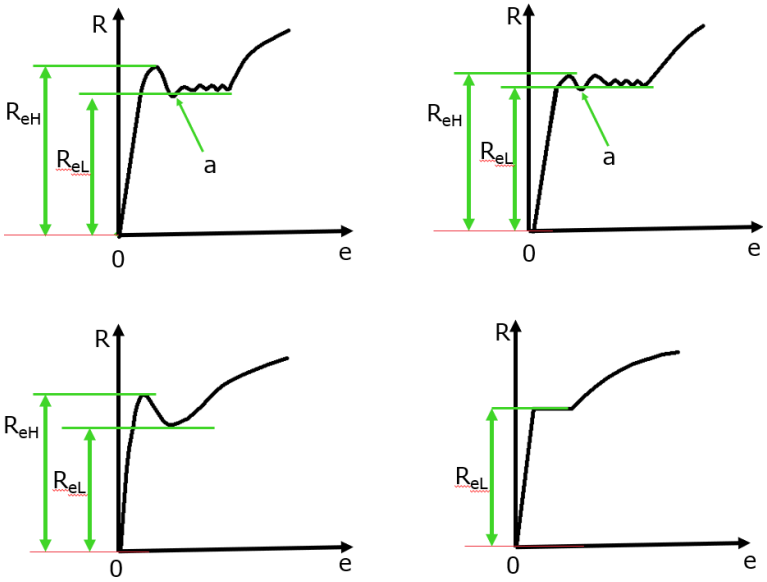
Figure 16: Proof strength, total extension, Rt [1].

- **Yield strength, R_e**

  Occurs when the metallic material exhibits a yield phenomenon, stress corresponding to the point reached during the test at which plastic deformation occurs without any increase int the force.

- **Upper yield strength, R_{eH}**
  Maximum value of stress prior to the first decrease in force

- **Lower yield strength, R_{eL}**
  Lowest value of stress during plastic yielding, ignoring any initial transient effects.



e – percentage extension,

R – stress,

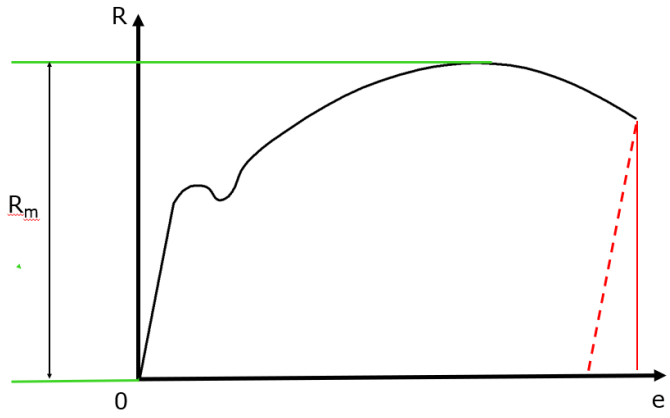
R_{eH} – upper yield strength,

R_{eL} – lower yield strength,

a – initial transient effect.

Figure 17: Examples of upper and lower yield strengths for different types of curves [1].

- **Tensile strength, R_m**
  Stress corresponding to the maximum force



e – percentage extension,

R – stress,

R_m – tensile strength,

Figure 18: Example of tensile strength [1].

2.1.1.2.2. Test pieces

a) Shape and dimensions

Shape and dimensions of the pieces may be constrained by the shape and dimensions of the metallic product from which the test pieces are taken. The sample for testing is most often prepared by machining from a product or semi-finished product. It is also possible to test components without being machined (e.g. tubes, wires, bars etc.).

Sample cross-sections can be circular, square, rectangular, annular or in special cases other shapes.

Preferred test specimens (proportional test pieces) should have a defined relationship between the original gauge length, L_0 and the original cross-section area, S_0 according to the formula:

$$L_0 = k \cdot \sqrt{S_0} \qquad (3)$$

where
k – coefficient of proportionality.

The most common value is **k=5.65**. In cases where the gauge length will be less than 15 mm, a higher value of **k=11.3** can be taken or a non-proportional sample can be made.

In the case of non-proportional samples, original gauge length L_0 does not depend from the original cross-section area S_o.

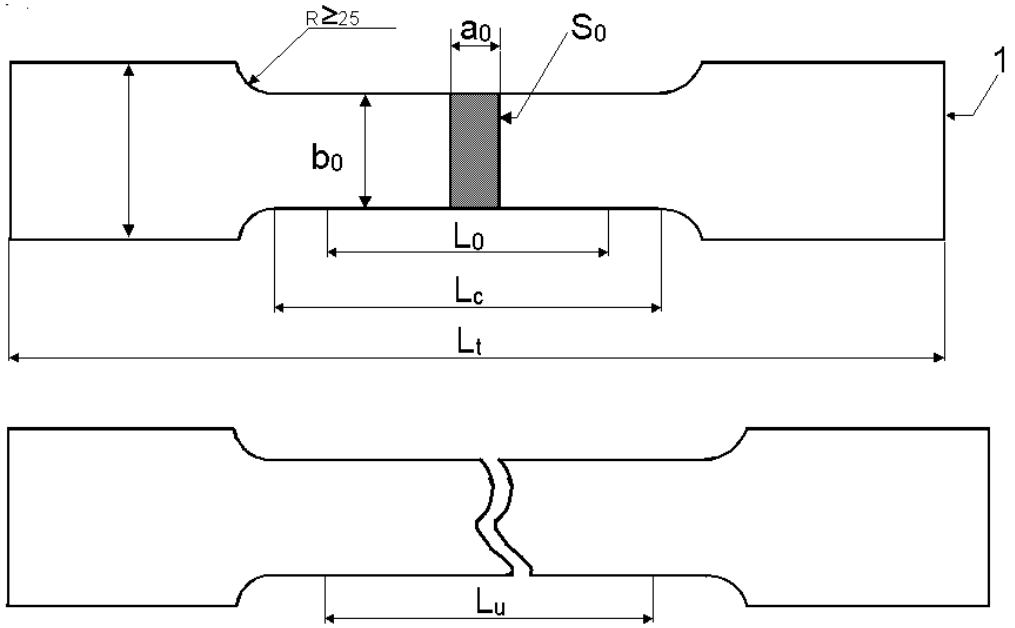


Figure 19: Machined test piece of rectangular cross-section [1].

a_0 – original thickness of a flat test piece or wall thickness of a tube
b_0 – original width of the parallel length of a flat test piece
L_c – parallel length
L_0 – original gauge length
L_t – total length of test piece
L_u – final gauge length after fracture
S_0 – original cross-section area of parallel length
1 – gripped ends

ISO 6892-1 also provides sample dimensions that can be used for various components. Table 1 summarises main types of test pieces according to product type.

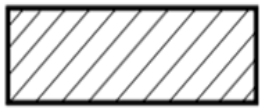
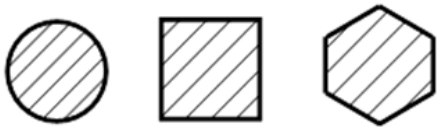
Type of product		Table
Sheets – Plates - Flats	Wire – Bars – Sections	
		
Thickness a, mm	Diameter or side Mm	
0,1≤ a < 3	-	Table 2
-	< 4	Table 3
A ≥ 3	≥ 4	Table 4
Tubes		Table 5

Table 1: Main types of test pieces according to product type.

Test piece type	Width b_0	Original gauge length L_0	Parallel length L_c		Free length between the grips for parallel sided test piece
			Minimum	Recommended	
1	12.5 ± 1	50	57	75	87.5
2	20 ± 1	80	90	120	140
3	25 ± 1	50[1]	60[1]	-	Not defined
Tolerances on the width of the test piece					
Nominal width of the test piece			Machining tolerance[2]		Tolerance on shape[3]
12.5			±0.05		0.06
20			±0.10		0.12
25			±0.10		0.12

[1]The ratio L_0/b_0 of a type 3 test piece in comparison to one of types 1 and 2 is very low. As a result, the properties, especially the elongation after fracture, measured with this test piece, will be different from other test piece types.
[2] These tolerances are applicable in nominal width of the test piece is to be used in the calculation of the original cross-sectional area S_0, without having to measure the width of each test piece.
[3] Maximum deviation between the measurements of the width along the entire parallel length L_c, of the test piece

Table 2: Dimensions and tolerances of test pieces for thin products: sheets, stripes and flats between 0.1 mm and 3 mm thick.

1.	The original gauge length, L_0, shall be taken as: - 200 mm ± 2 mm - 100 mm ± 1 mm
2.	The distance between the grips of the machine shall be equal to at least $L_0 + 3b_0$, but minimum of $L_0 + 20$ mm.
3.	If the percentage elongation after fracture is not to be determined, a distance between the grips of at least 50 mm may be used.
4.	Determine S_0 to an accuracy of ± 1 % or better For products of circular cross-section, the original cross-sectional area may be calculated from the arithmetic mean of two measurements carried out in two perpendicular directions.
5.	The original cross-sectional area, S_0, in square millimetres, may be determined from the mass of a known length and its density: $$S_0 = \frac{1000 \cdot m}{\rho \cdot L_t} \quad (4)$$ m, mass, in grams, of the test piece, ρ, is the density, in grams per cubic centimetre, of test piece material, L_t is the total length, in millimetres, of the test pieces.

Table 3: Dimensions and tolerances of test pieces for wire, bars and sections with diameter or thickness of less than 4 mm.

1.	The minimum transition radius between the gripped ends and the parallel length shall be: - $0.75d_0$ where d_0 is the diameter of the parallel length, for the cylindrical test piece, - 0,12 mm for other test pieces.
2.	The cross-section of the test piece may be: circular, square, rectangular or another shape,
3.	For test pieces with rectangular cross-section, the width to thickness ratio should not exceed 8:1
4.	The diameter of the parallel length of machined cylindrical test piece shall be not less than 3 mm.
5.	The parallel length, L_c, shall be at least equal to: $L_0 + \left(\frac{d_0}{2}\right)$ $for\ cylindrical\ tes\ piece$ $L_0 + 1.5\sqrt{S_0}$ $for\ proportional\ test\ pieces\ other\ than\ cylindrical\ tes\ pieces$ $L_0 + \left(\frac{b_0}{2}\right)$ $for\ non-proportional\ tes\ pieces$ In case of dispute, the length L_0+2d_0 or $L_0+2\sqrt{S_o}$ shall be used depending on the type of test piece, unless there is insufficient material
6.	The free length between grips of the machine shall be adequate for marks to be at least a distance of $\sqrt{S_o}$from the grips.
7.	As a general rule, proportional test pieces are used where L_0 is related to the original cross-sectional area S_0, $L_0 = k\sqrt{S_0}$, where k is equal to 5,65. Alternatively, 11.3 may be used as the k value.

Circular cross-section test pieces			
Coefficient of proportionality, k	Diameter, d, mm	Original gauge length, $L_0 = k\sqrt{S_0}$, mm	Minimum parallel length, L_c, mm
5.65	20	100	110
	14	70	77
	10	50	55
	5	25	28
Non-proportional test pieces			
Non proportional test pieces may be used if specified by the product standard. The parallel length, L_c, should not be less than $L_0 + b_0/2$. In case of dispute, the parallel length $L_c = L_0 + 2b_0$ shall be used unless there is insufficient material			
Typical flat test piece dimensions			
Width, b_0, mm	Original gauge length, L_0, mm	Minimum parallel length L_c, mm	Approximately total length L_t, mm
40 ± 0.7	200	220	450
25 ± 0.7	200	212,5	450
20 ± 0.5	80	90	300

Table 4: Dimensions and tolerances of test pieces for sheets and flats thickness equal to or greater than3 mm and wires, bars and sections of diameter or thickness equal to or greater than 4 mm.

1. The tube length may be plugged at both ends. The free length between each plug and the nearest gauge marks shall be greater than $D_0/4$. In case of dispute the value D_0 shall be used, if there is sufficient material.
2. The length of the plug projecting beyond the grips of the machine in the direction of the gauge marks shall not exceed D_0, and its shape shall be such that it does not interfere with deformation of the gauge length.
3. The parallel length L_c, of the longitudinal strips shall not be flattened byt the heads may be flattened for gripping in the testing machine
4. S_0 for the test piece shall be determined to the nearest ±1 % or better.
5. The original cross-sectional area, S_0, in square millimetres, of the length of tube or longitudinal or transverse strip may be determined from the mass of the test piece, the length of which has been measures and from its density:

$$S_0 = \frac{1000 \cdot m}{\rho \cdot L_t} \qquad (4)$$

m, mass, in grams, of the test piece,

ρ, is the density, in grams per cubic centimetre, of test piece material,

L_t is the total length, in millimetres, of the test pieces.

6. The original cross-sectional area S_0, of a test piece consisting of a longitudinal sample shall be calculated according to:

$$S_0 = \frac{b_0}{4}(D_0^2 - b_0^2)^{\frac{1}{2}} + \frac{D_0^2}{4}\arcsin\left(\frac{b_0}{D_0}\right) - \frac{b_0}{4}[(D_0 - 2a_0)^2 - b_0^2]^2 - \left(\frac{D_0 - 2a_0}{2}\right)^2 arcsin\left(\frac{b_0}{D_0 - 2a_0}\right) \qquad (5)$$

7.	The simplified formula can be used for longitudinal test pieces where the ratio between width and external tube diameter falls below set limits: $S_0 = a_0 b_0 \left[1 + \frac{b_0^2}{6D_0(D_0 - 2a_0)}\right] \quad if \ \frac{b_0}{D_0} < 0.25$ (6) $S_0 = a_0 b_0 \quad if \ \frac{b_0}{D_0} < 0.10$ (7)
8.	For length of tube, the original cross-section area S_0 shall be calculated from $S_0 = \pi a_0 (D_0 - a_0)$ (8)

Table 5: Dimensions and tolerances of test pieces for tubes.

2.1.1.2.3. Conditions of testing

a) Setting of the force zero point

The force-measuring system shall be set to zero after testing loading train has been assembled, but before the test piece is actually gripped at both ends. Once the force zero point has been set, the force-measuring system shall not be changed in any way during the test.

b) Method of gripping

The test pieces shall be gripped by suitable means, such as wedges, screwed grips, parallel jaw faces or shouldered holder.

Every endeavour should be made to ensure that test pieces are held in such a way that the force is applied as axially as possible in order to minimize bending. This is of particular importance when testing brittle materials or when determining proof strength (plastic extension), proof strength (total extension) or yield strength.

In order to ensure the alignment to the test piece and grip arrangement, a preliminary force may be applied provided it does not exceed a value corresponding to 5 % of the specified or expected yield strength. A correction of the extension should be carried out to take into account the effect of the preliminary force.

c) Testing rates

Unless otherwise agreed the choice of the method (A1, A2 or B) and test rates are at the direction of the procedure or the test laboratory assigned by the producer.

<u>Method A – Testing rate based on strain rate</u>

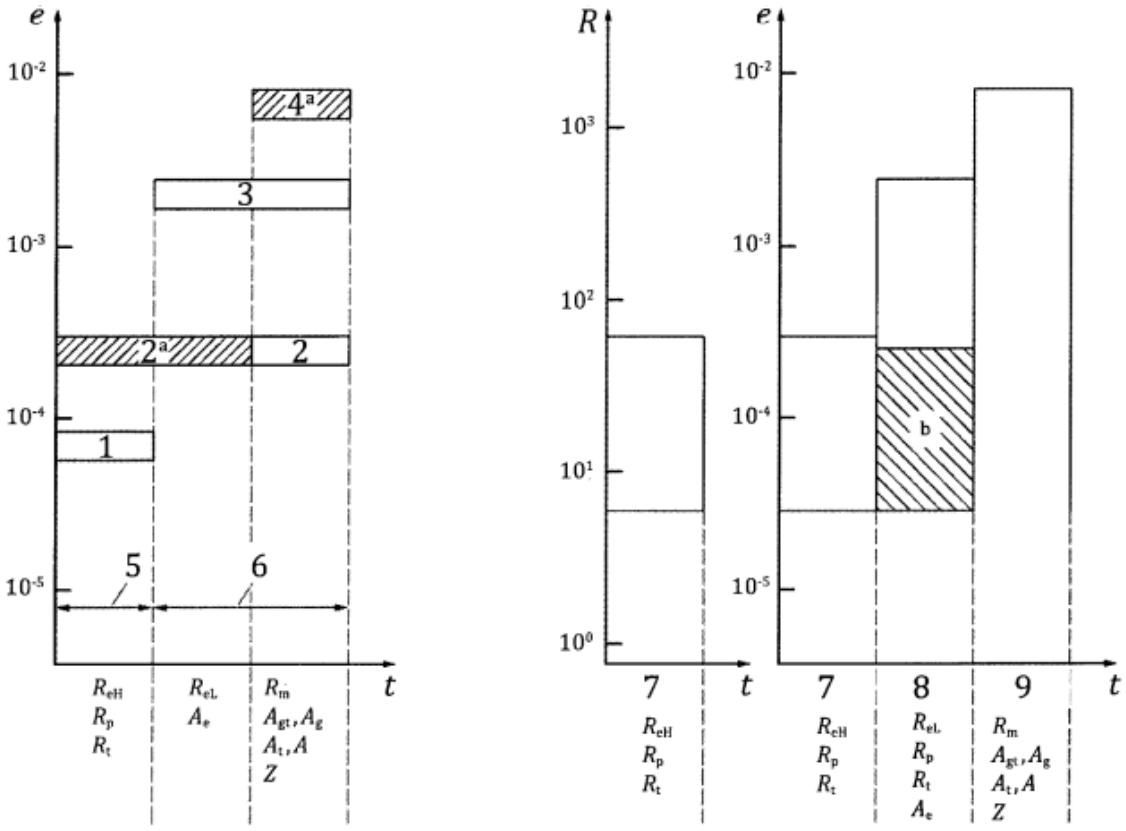
This method is intended to minimize the variation of the test rates during the moment when strain rate sensitive parameters are determined and to minimize and minimize the measurement uncertainty of the test results.

There are two different types of strain rate control:

A1 – closed loop involves the control of the strain rate itself, $\dot{e}_{L_e}$, that is based on the feedback obtained from an extensometer.

A2 – open loop involves the control of the estimated strain rate over parallel length $\dot{e}_c$, which is achieved by using the crosshead separation rate calculate by multiplying the required strain rate by the parallel length.

The strain rate shall be maintained during the determination of the relevant material property.



a) Method A **b) Method B**

Key

$\dot{e}$ strain rate, in s^{-1}

$\dot{R}$ stress rate, in MPa s^{-1}

t time

1 range 1: $\dot{e}$ = 0,000 07 s^{-1}, with a relative tolerance of ±20 %

2 range 2: $\dot{e}$ = 0,000 25 s^{-1}, with a relative tolerance of ±20 %

3 range 3: $\dot{e}$ = 0,002 s^{-1}, with a relative tolerance of ±20 %

4 range 4: $\dot{e}$ = 0,006 7 s^{-1}, with a relative tolerance of ±20 % (0,4 min^{-1}, with a relative tolerance of ±20 %)

5 control mode: extensometer control (Method A1 closed loop) or crosshead control (Method A2 open loop)

6 control mode: crosshead control (Method A2 open loop)

7 elastic range of the test

8 plastic range for the determination of R_{eL}, R_p, R_t, A_e

9 maximum strain rate for the determination of R_m, A_{gt}, A_g, A_t, A, Z

a Recommended.

b Expanded range to lower rates, if testing machine is not capable of measuring or controlling the strain rate (see 10.3.3.2.5).

NOTE 1 Symbols refer to Table 1.

NOTE 2 Strain rate in the elastic range for method B is calculated from stress rate using a Young's modulus of 210 000 MPa (steel).

Figure 20: Illustration of strain rates to be used during tensile test (method A).

Method B – Testing rate based on stress rate

The testing rates shall conform to the following requirements depending on the nature of the material. Unless otherwise specified, any convenient speed of testing may be used up to a stress equivalent to half of the specified yield strength.

- Upper yield strength, R_{eH}
  The rate of separation of the crossheads of the machine shall be kept as constant as possible and within the limits corresponding to the stress rates:

Modulus of elasticity of the material E MPa	Stress rate $\dot{R}$ $MPa\ s^{-1}$	
	min.	max.
<150 000	2	20
≥150 000	6	60

Table 6: Stress rate.

- Lower yield strength, R_{eL}
  If only the lower yield strength is being determined, the strain rate during yield of the parallel length of the test piece shall be between:
  0.0 25s^{-1} and 0.002 5 s^{-1}
  The strain rate within the parallel length shall be kept as constant as possible. If this rate cannot be regulated directly, it shall be fixed by regulating the stress rate just before yield begins, the control of the machine not being further adjusted until completion of yield.

  In case shall the strass rate in the elastic range exceed the maximum rates in Table 6.

d) Determination of the upper and lower yield strength, R_{eH}, R_{eL}

R_{eH}, R_{eL} may be determined from the force-extension curve or peak load indicator according to figure 17. The value is calculated by dividing the force by original cross-sectional area of the test piece, S_0.

e) Determination of proof strength, plastic extension, R_p

R_p is determined from the force-extension curve by drawing a line parallel to the linear portion of the curve and at a distance from it equivalent to the prescribed plastic percentage extension, e.g. 0.2 %. The point which this line is intersect the curve gives the force corresponding to the desired proof strength plastic extension (figure 15). The latter is obtained by dividing this force by the original cross-sectional area of the test piece, S_0.

f) Determination of proof strength, total extension, R_t

Rt is determined from the force-extension curve by drawing a line parallel to the ordinate axis (force axis) and at a distance from this equivalent to the prescribed total percentage extension. The point which this line is intersect the curve gives the force corresponding to the desired proof strength (figure 16). The value is calculated by dividing this force by the original cross-sectional area of the test piece, S_0.

2.1.1.2.4. Description of the test (step-by-step)

a) Preparing samples in accordance with point 3.2 of the procedure

- The samples shall be visually inspected and the presence of any imperfections on the measuring surface should be noted in the test report.
- Measure The specimen dimensions in accordance with point 3.2 of the procedure
- Determine the measurement bases on the specimen in accordance with the guidelines in point 3.1 Principle – Percentage elongation after fracture – A of the procedure

b) Preparing the testing machine

- check zero position of force gauges (point 3.3 a))
- select the tensile strength (point 3.3 c))
- place the specimen in the machine

c) Perform the tensile test

- The test shall be carried out in accordance with the provisions of the Standard ISO 6892-1 and the guidelines given in this document.
- The method of testing on individual machines depends on the equipment available. Operating instructions must be provided for the machine available.

d) Test report

The test report shall contain at least the following information, unless otherwise agreed by the parties concerned:

- Reference to standard or this document, extended with the test condition information,
- Identification of the test piece
- Specified material if know
- Type of test piece
- Location and direction of sampling of the test piece, if know

- Testing control mode and testing rate or testing rate range if different from the recommended methods (A or B)
- Test results (results should be rounded to the following precisions or better, if not otherwise specified in product standards: strength values in MPa to the nearest whole number, percentage yield point values Ae, to the nearest 0,1 %, all other percentage extension and elongation values to the nearest 0,5%, percentage reduction of area Z, to the nearest 1 %.

2.1.1.3. References

[1] EN ISO 6892-1: “Metallic materials. Tensile testing. Method of test at room temperature”

[2] EN ISO 6892-2: “Metallic materials. Tensile testing. Method of test at elevated temperature”

[3] ASTM E8: “Standard Test Methods for Tension Testing of Metallic Materials”

2.2. Tensile Tests of Welded Joints with Butt Welds, Cruciform Joints, Overlap Joints, and Joints with Fillet Welds

2.2.1. Introduction

Welded joints are widely used in various industries such as construction, manufacturing, and transportation. The mechanical properties of welded joints are crucial in determining the structural integrity and safety of the components they are used in. Tensile test of welded joints in one of the most important destructive test in welding industry. It is mainly used for purposes of welding procedure specification qualification in accordance to standards like EN ISO 15614 series as well as ASME BPVC Section IX. However, qualification of welding procedures is not only application of tensile test in welding industry. Tensile test can also be used to verify mechanical properties of welding consumables or to confirm welding joint quality in production according to e.g. product specifications.

The principle of the test is same as tensile test of metallic materials, therefore unless otherwise specified for specific points the general rules of EN ISO 6892-1 [1] and EN ISO 6892-2 [2] applies. These rules are covered in Chapter 2.1 of this Handbook.

There are several types of tensile tests of welded joints. These are mostly dependent on the type of joint. This chapter will cover some of most popular types:

- Transverse tensile test of welded joints
- Longitudinal tensile test on weld
- Tensile test on cruciform an lapped joints

The main differences between these tests are specimen location, specimen geometry and test results reported.

2.2.2. Tensile test of welded joints

2.2.2.1. Transverse tensile test of welded joints (EN ISO 4136)

The test specimen shall be taken transversely from the welded joint in such way that, after machining, the weld axis remains in the middle of the parallel length of the test specimen. For small diameter pipes the test may be caried out on whole pipe, if not specified by the application standards or agreed upon between the contracting parties, “small diameters” means D ≤ 50 mm. The processes used to extract test specimen shall not change the properties of the test specimen in any way. The final parallel length of test specimen should be machined (sawing, milling, water-jet cutting) or grinded. The surfaces shall be free from scratches or notches transverse to the test specimen direction in the parallel length, L_c, except for undercut which shall not be removed unless required by the relevant application standard. Unless otherwise specified all excess weld should be removed, except penetration bead in full section pipes. The thickness of the test specimen shall be constant along parallel length, the shape and dimensions shall conform to those given in In Table 7 with reference to the symbols given in Figure 22. The dimensions for full section pipe test specimens are shown in Figure 23.

In general, the thickness of the test specimen, ts shall be equal to the thickness of the parent metal near the welded joint, however in cases when testing of full thickness > 30 mm is required, several test specimens may be taken to cover full thickness of the joint (see Figure 21).

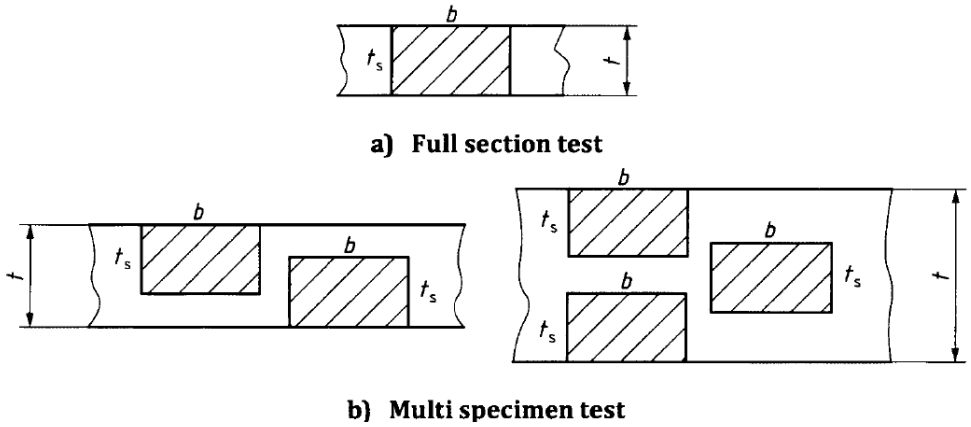


Figure 21: Examples of location of test specimens in joints. The test specimens can overlap.

Denomination		Symbol	Dimension in mm
Total length of the test specimen		L_t	to suit particular testing machine
Width of shoulder		b_1	b+12
Width of parallel length	plates	b	12 for $t_s \leq 2$ 25 for $t_s > 2$
	pipes	b	6 for D ≤ 50 12 for D < 50 ≤ 168,3 25 for D > 168,3
Parallel length		L_c	$\geq L_s + 60$
Radius at shoulder [a] [b]		r	≥ 25
[a] For pressure welding and beam welding (process groups 2, 4 and 5 in accordance with ISO 4063, $L_s = 0$. [b] For some other metallic materials (e.g. aluminium, copper and their alloys $L_c \geq L_s + 100$ may be necessary			

Table 7: Dimensions for plates and pipes.

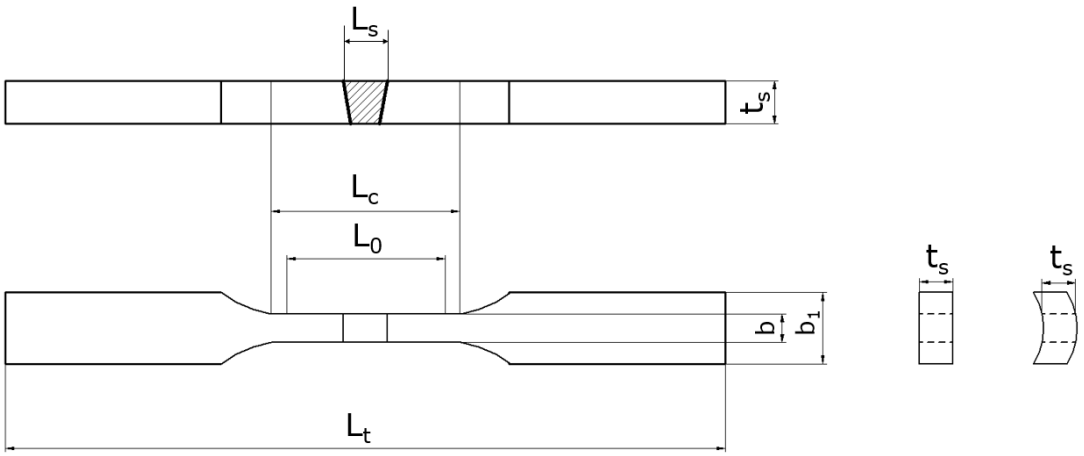


Figure 22: Test specimen for plates or pipes.

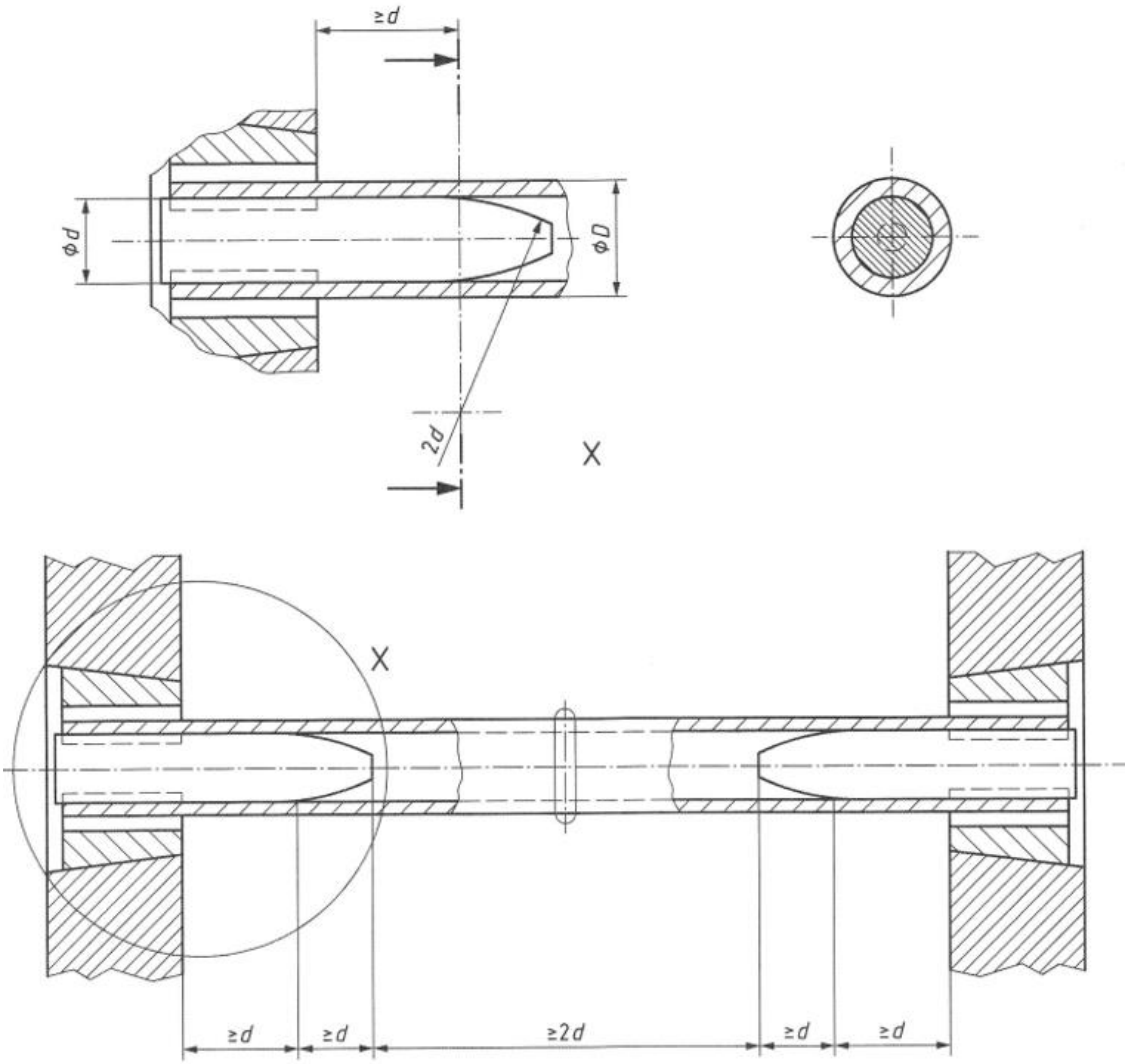


Figure 23: Test specimen for full section pipe.

The test specimen shall be loaded gradually and continuously until fracture in accordance with ISO 6892-1 standard. The test results consist of tensile strength of welded joint R_m, determined in accordance with ISO 6892-1 and location of fracture. The fracture can occur in one of three materials: weld metal, heat affected zone (HAZ) or parent metal. If necessary to assist location of weld and HAZ, the side of the test specimen may be macro etched. The desired result is rupture in the parent material and achievement of a tensile strength at least equal to the tensile strength of the parent material. If rupture of the test piece occurs in the weld metal or the HAZ and the corresponding tensile strength is reached, the test result is also positive. Figure 24 shows a diagram of the joint with possible causes of specimen rupture in the weld or heat affected zone.

After rupture of the test specimen, the fractured surfaces shall be examined and the existence of any imperfections that may have adversely affected the test shall be recorded, including their type, size and quantity.

The test report shall include following information:

- reference to ISO 4136 standard,
- type and location of test specimen,

- test temperature,
- test results,
- location of fracture,
- type and dimensions of imperfections observed.

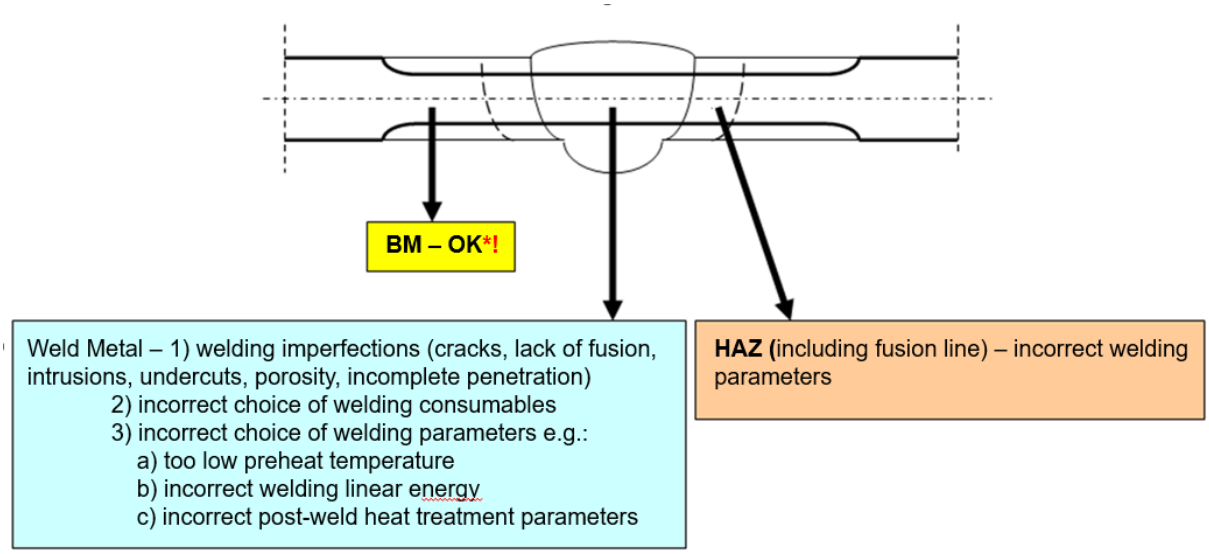
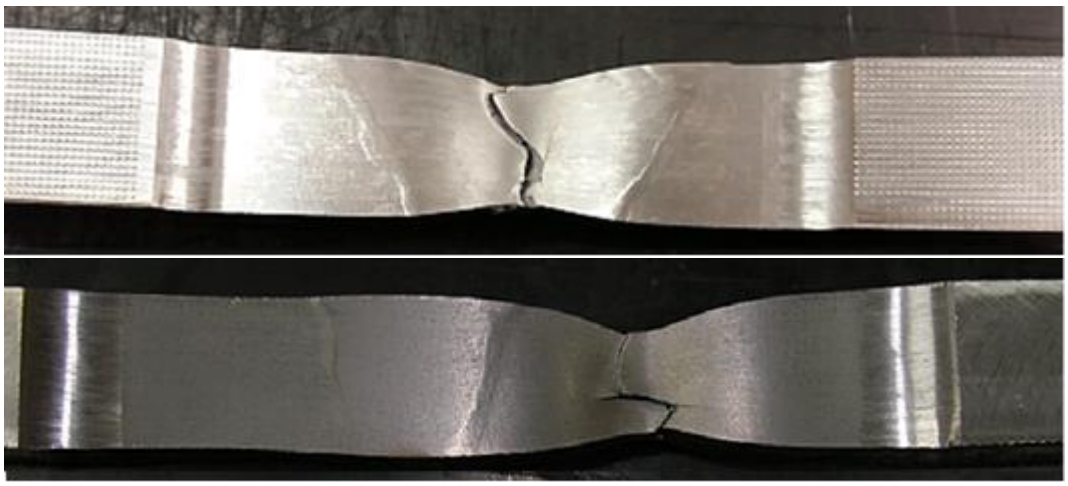


Figure 24: Diagram of the joint in test specimen. Possible causes of fracture in weld metal or HAZ.

a)

b)



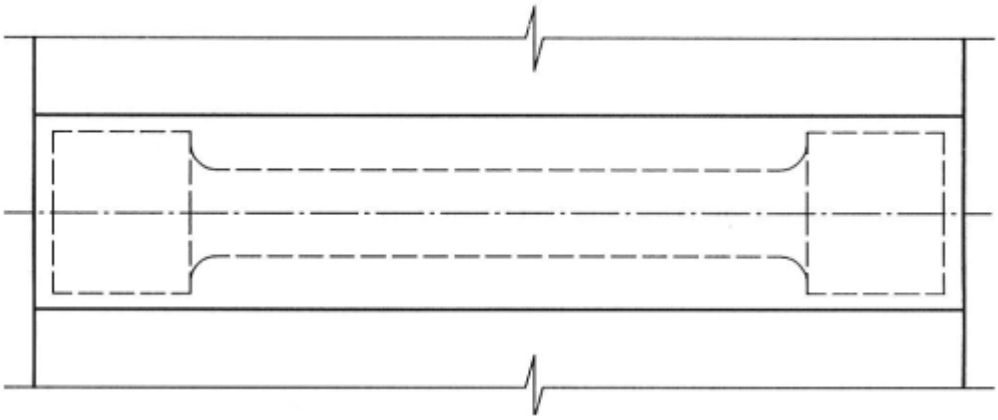
c)

Figure 25: Examples of specimens after breakage.

2.2.2.2. Longitudinal tensile test on weld metal (EN ISO 5178)

The test specimen shall be taken longitudinally from the welded joint of the manufactured product or from the test piece. After machining, the parallel length of the test specimen shall consist only of weld metal. To enable correct positioning of the test specimen in the joint, the joint cross-section at both ends of the test specimen can be macro etched. Unless otherwise specified in the particular application standard dealing with the welded joint under examination, the test specimens shall be taken from the centre of the weld metal as shown in Figure 26. In the case where the test specimen is not taken from mid-thickness, the distance from the surfaces, t_1, shall be recorded. In the case of very thick or double-sided welded joint, more than one test specimen may be taken at different locations through the thickness, in which case the distances, t_1 and t_2, of each test specimen in the joint cross-section shall be recorded.

a)



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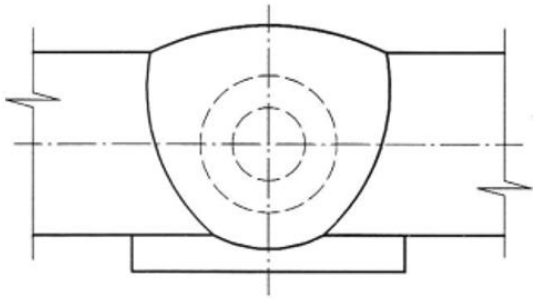
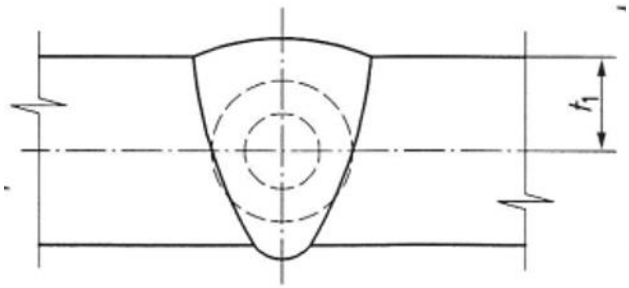


c)



d)

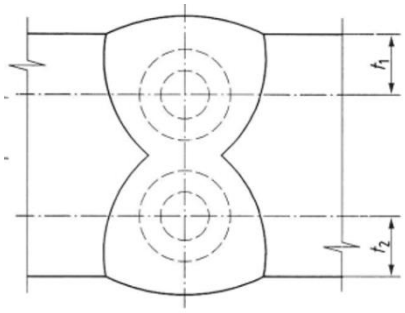


Figure 26: Examples of location of test specimens: a) longitudinal plane section, b) all-weld metal test specimen for welding consumable classification, c) test specimen from a single-side welded joint, d) test specimen form a joint welded from both sides.

Each test specimen shall have a circular cross-section and its dimensions, expressed as functions of the diameter, d_0, of the parallel length shall conform to ISO 6892-1. If possible diameter d_0 shall have dimension of 10 mm. If this is not possible, the diameter shall be as large as possible but not less than 4 mm. The gripped ends of the test specimens are not described in ISO 5178 standards, thus should be compatible with used tensile testing machine.

The test specimen shall be loaded gradually and continuously until fracture and test result shall be determined in accordance with ISO 6892-1. As the specimen consist only of weld metal (unlike transverse tensile test where it consists of weld metal, HAZ and parent metal) test result should consist of proof strength plastic extension R_p (or yield strength R_e, proof strength total extension R_t), tensile strength R_m, elongation after fracture A and reduction of area Z. After rupture of the test specimen, the fractured surfaces shall be examined and the existence of any imperfections that may have adversely affected the test shall be recorded, including their type, size and quantity.

The test report shall include following information:

- reference to ISO 4136 standard,
- type and location of test specimen,
- test temperature,
- test results,
- location of fracture,
- type and dimensions of imperfections observed
- diameter d_0.

2.2.2.3. Tensile test on cruciform and lapped joints (EN ISO 9018)

This standard describes a tensile test for two types of joint: a cruciform joint and a lap joint. Both types of joints consist of several fillet welds that has to be measured prior to testing. Location and geometry with dimensions of specimens are presented in Figures 27 to 31.

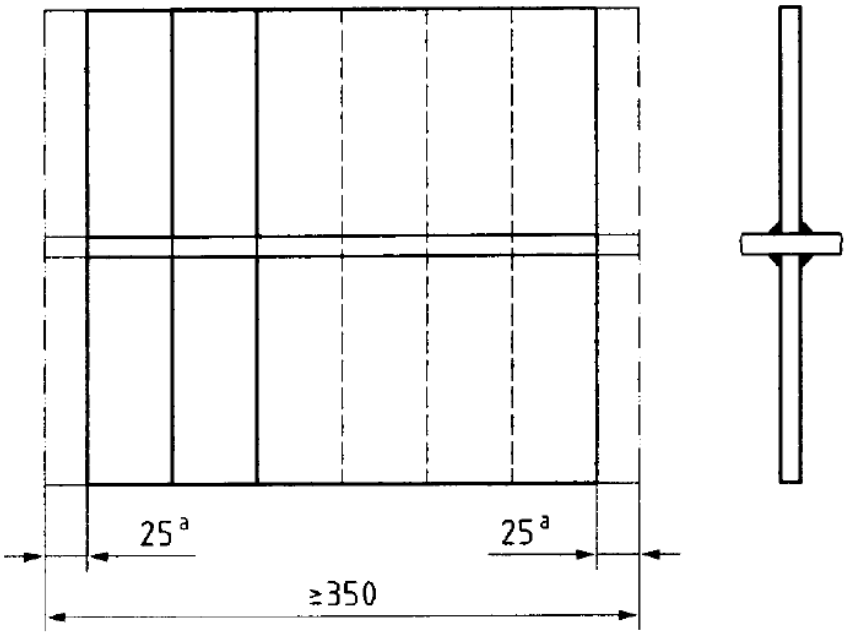


Figure 27: Location of specimen from a cruciform joint. a End pieces are to be discarded.

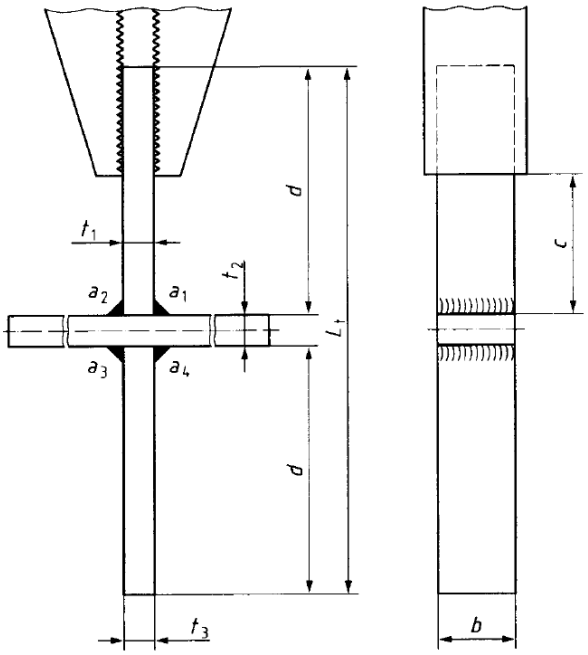


Figure 28: Cruciform joint test specimen.

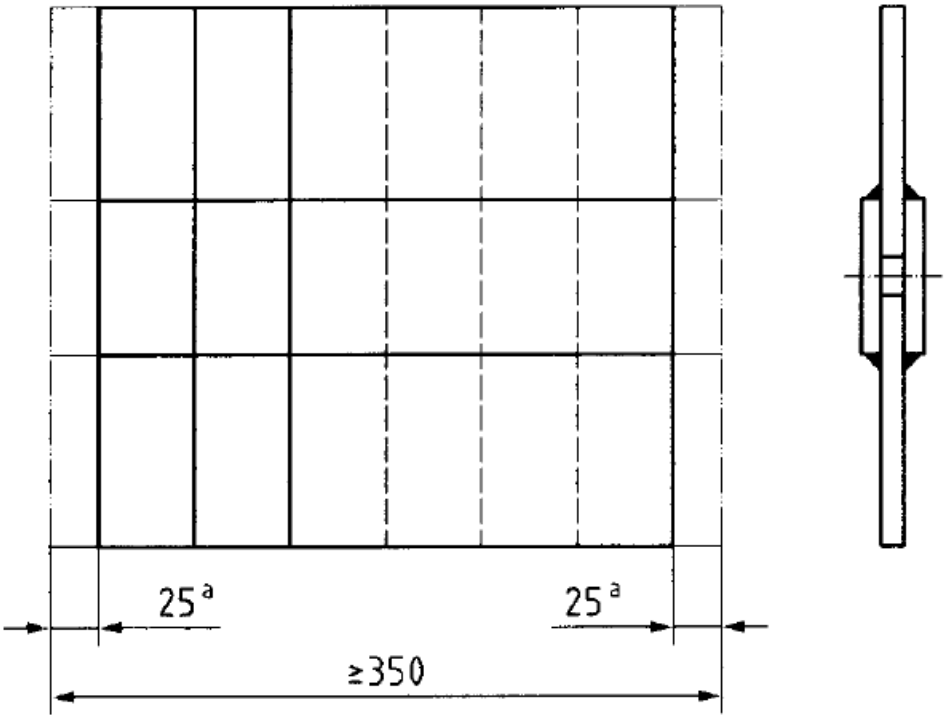


Figure 29: Location of specimen from a lapped joint. a End pieces are to be discarded.

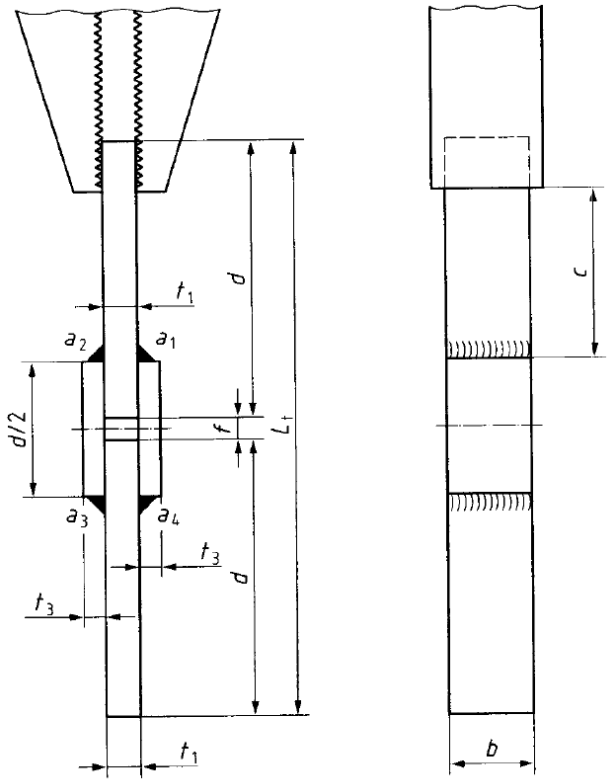


Figure 30: Lapped joint test specimen.

Prior to testing, the dimensions of the test pieces shall be measured and recorded. The test specimen shall be loaded gradually and continuously in a direction perpendicular to the weld axis until rupture

occurs. The speed of loading shall be as uniform as possible, testing shall be progressive and without abrupt changes.

After testing the following shall be measured and recorded:

- the test temperature, T,
- the fracture surfaces shall be examined and the existence of any imperfection, including their type, size and amount,
- the average width of the fracture surface w_f shall be determined by measuring at several point across the fracture at a spacing of approximately 3×a and dividing by the total number of measurements,
- the tensile strength R_m, calculated as the ratio of the maximum load Fm, sustained by the test specimen during testing and fracture area A_f expressed in MPa.

The width of fracture surface shall be measured as shown in Figure 31.

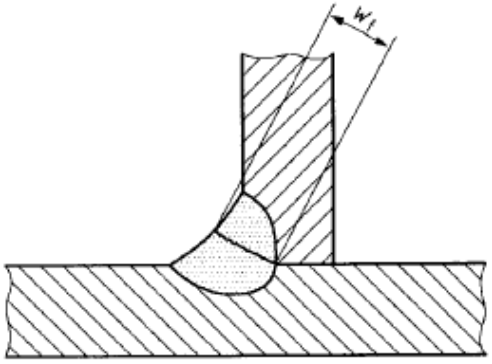


Figure 31: Definition of width of fracture surface.

The surface of fracture A_f shall be calculated using the formula:

$$A_f = w_f * b \quad (1)$$

The test report shall include the following information:

- reference to ISO 9018,
- date of testing,
- detail concerning the examiner or test body,
- dimensions of test specimen before fracture (a_1, a_2, a_3, a_4, t_1, t_2, t_3, b),
- amount of misalignment and angular distortion,
- location of the fracture,
- location, type, size and amount of any imperfections,
- average width of the fracture Surface w_f,
- tensile strength R_m,
- load per unit length F_m/b,
- test temperature,
- details of any heat treatment in accordance with the relevant application standard.

2.2.3. References

[1] EN ISO 6892-1: “Metallic materials. Tensile testing. Method of test at room temperature”.

[2] EN ISO 6892-2: “Metallic materials. Tensile testing. Method of test at elevated temperature”.

[3] EN ISO 4136: “Destructive tests on welds in metallic materials. Transverse tensile test”.

[4] EN ISO 5178: “Destructive tests on welds in metallic materials. Longitudinal tensile test on weld metal in fusion welded joints”.

[5] EN ISO 9018: “Destructive tests on welds in metallic materials. Tensile test on cruciform and lapped joints”.

2.3. Bend Tests of Metals and Welded Joints

2.3.1. Foreword

The Bend Test is a simple and very important test to assess the ductility and the absence of imperfections on a welded joint or a cladding made by any fusion arc welding process. The recording of the load and the deflection (or displacement) during the test is not necessary, indeed just a visual check is performed after the execution of the test. The lone measurable datum is the elongation; such result is calculated from the difference between a reference measure before (initial) and after the test, then such difference is divided by the initial reference to obtain a percentage. Typically, the bend test is performed on 4 specimens, taken with specific orientation on the basis of the application standard or by agreement between the contracting parties. Basically, the bend test is a crucial test to qualify a fusion welding process on a go no-go basis.

In this chapter the standard test method to perform the bend test (ISO 5173) is reported and described.

2.3.2. References

- ISO 5173Destructive tests on welds in metallic materials — Bend tests —Amendment 1
- ASTM E340 Standard Practice for Macroetching Metals and Alloys
- ISO 6892-1 Metallic materials — Tensile testing — Part 1: Method of test at room temperature
- ISO 15614-1 Specification and qualification of welding procedures for metallic materials — Welding procedure test — Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys

2.3.3. Introduction

The bend test has the scope to assess ductility and/or absence of imperfections on or near the surface of the test specimen. Submitting a test specimen, taken transversely or longitudinally from a welded joint, to plastic deformation by bending it, without reversing the bending direction, in such a way that one of the surfaces or cross-sections of the welded joint is in tension.

Unless otherwise specified, the test shall be carried out at an room temperature of (23 ± 5) °C.

In the following table, the list of terms adopted in ISO 5173 are reported together with their descriptions and definitions (see Table 8).

The figures cited in Table 8 are reported below the table.

Term	Definition	Description
TFBB	Transverse face bend test specimen for a butt weld	Specimen for which the surface in tension is the side that contains the greater width of the weld or the side from which the welding arc was first applied, applicable to transverse butt weld specimens. See Figure 32.
TRBB	Transverse root bend test specimen for a butt weld	Specimen for which the surface in tension is the side opposite to that of the face butt weld bend test specimen, applicable to transverse butt weld specimens. See Figure 33.
SBB	Transverse side bend test specimen for a butt weld	Specimen for which the surface in tension is a cross-section of the weld. See Figure 34.
LFBB	Longitudinal face test specimen for a butt weld	Specimen whose direction is parallel to butt weld direction, applicable to face and root bend specimens. See Figure 35.

LRBB	Root bend test specimen for a butt weld	Specimen whose direction is parallel to butt weld direction, applicable to face and root bend specimens. See Figure 35.
FBC	Face bend test specimen for cladding without a butt weld	Specimen for which the cladding is in tension, applicable to both transverse and longitudinal specimens. See Figure 36.
SBC	Side bend test specimen for cladding without a butt weld	Specimen for which the cross-section of the cladding overlay is in tension, applicable to both transverse and longitudinal specimens. See Figure 37.
FBCB	Face bend test specimen for cladding with a butt weld	Specimen for which the cladding is in tension or for which the cross-section of the cladding overlay is in tension and which contains a butt weld. See Figures 38.
SBCB	Side bend test specimen for cladding with a butt weld	Specimen for which the cladding is in tension or for which the cross-section of the cladding overlay is in tension and which contains a butt weld. See Figures 39.
A	Elongation	Minimum percentage elongation after fracture required by the material specification, measured in [%] according to ISO 6892-1
b	Width (specimen)	Width of the test specimen, measured in [mm]
b_1	Width (outside fusion line)	Width of outside fusion line, measured in [mm]
d	Diameter (former/roller)	Diameter of the former or the inner roller, measured in [mm]
D	Diameter (pipe)	Outside diameter of the pipe, measured in [mm]
wt	Wall thickness	Wall thickness of the pipe, measured in [mm]
l	Length (gap)	Distance between the rollers, measured in [mm]
L_f	Distance	Initial distance between contact of the roller and the centre line of the weld, measured in [mm]
L_0	Gauge length	Original gauge length, measured in [mm]
L_s	Width of weld	Maximum width of the weld after machining, measured in [mm]
L_t	Length of specimen	Total length of the test specimen, measured in [mm]
r	Radius	Radius of the test specimen edges, measured in [mm]
R	Radius	Radius of the rollers, measured in [mm]
t	Thickness (piece)	Thickness of the test piece, measured in [mm]
t_c	Thickness (clad)	Thickness of the cladding, measured in [mm]
t_s	Thickness (specimen)	thickness of the test specimen, measured in [mm]
t_w	Thickness (base material)	Thickness of base material under cladding, measured in [mm]
α	Angle	Bending angle, measured in [°]

Table 8 -List of terms and definitions taken from ISO 5173.

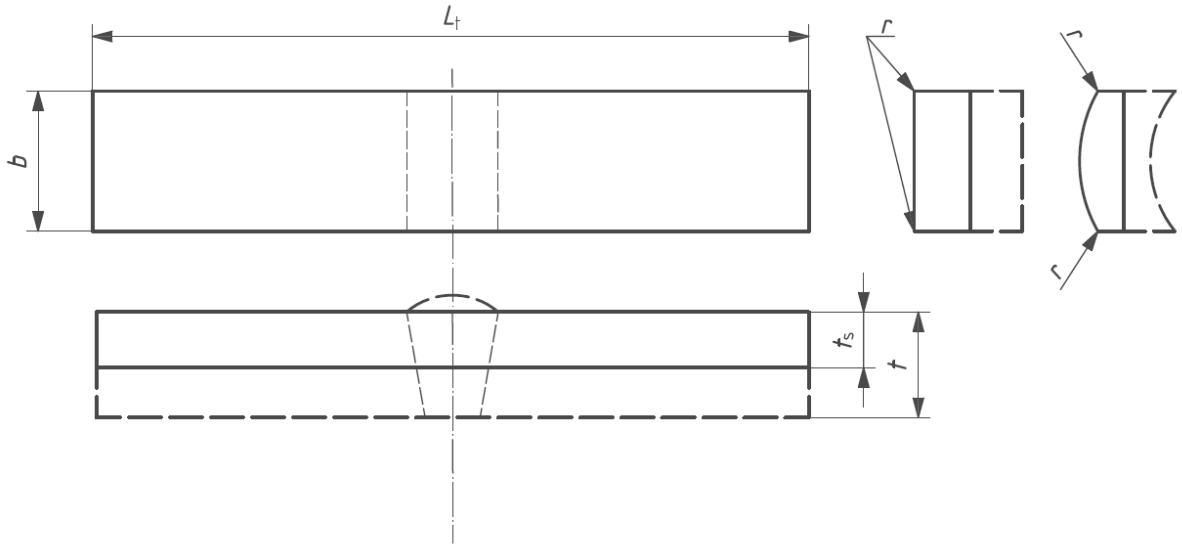


Figure 32 - Transverse face bend test specimen for a butt weld (TFBB).

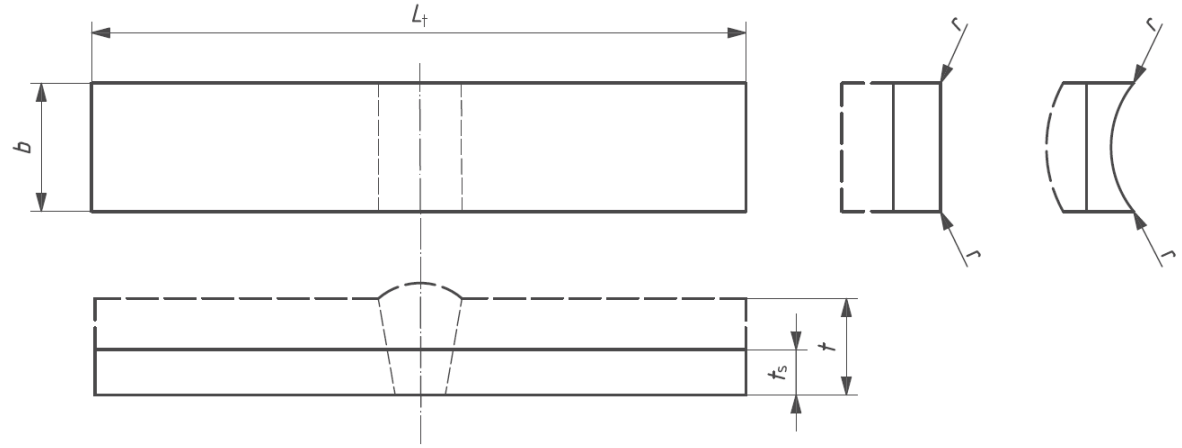


Figure 33 - Transverse root bend test specimen for a butt weld (TRBB).

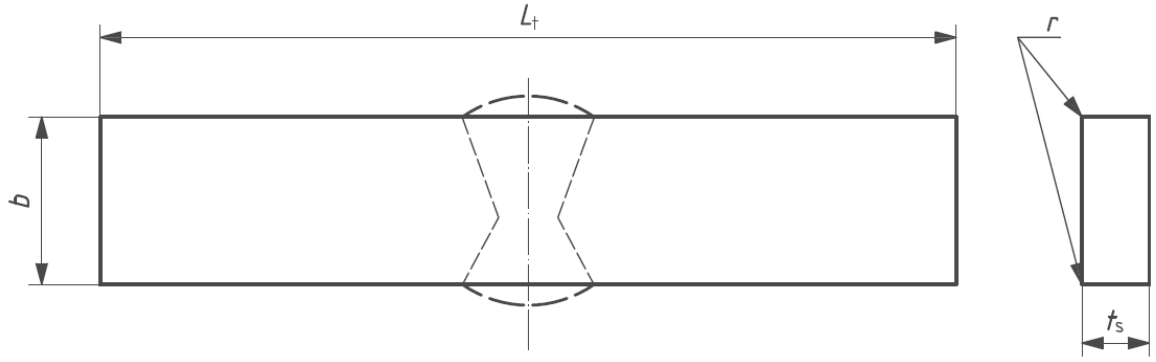


Figure 34 - Transverse side bend test specimen for a butt weld (SBB).

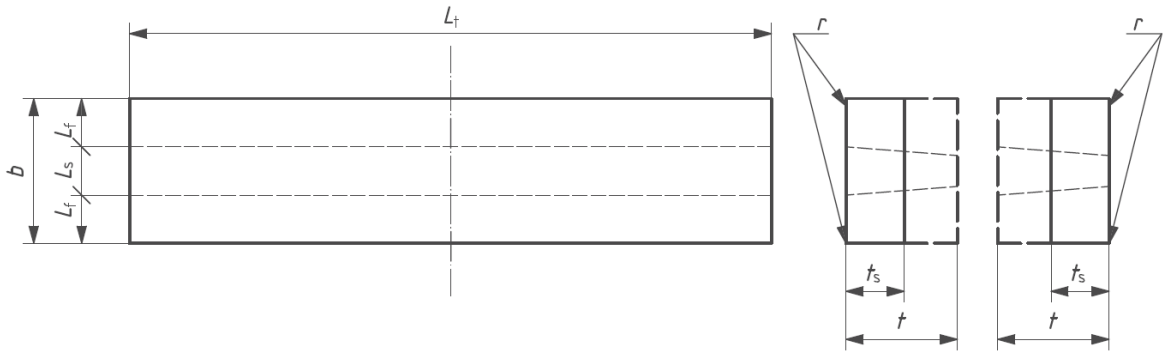


Figure 35 - Longitudinal bend test specimen for a butt weld (LFBB and LRBB).

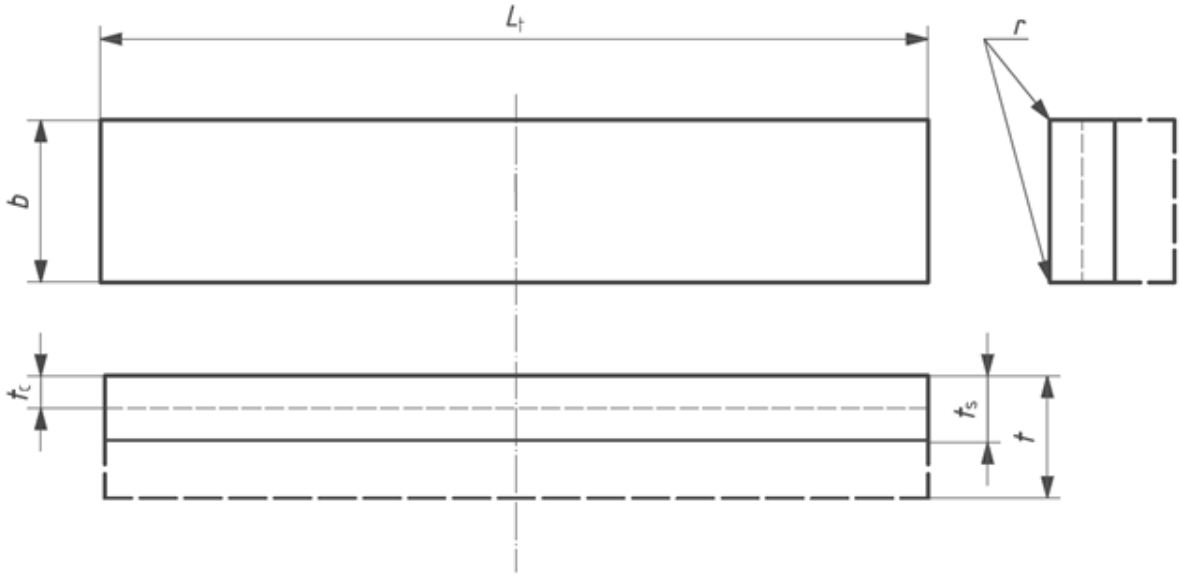


Figure 36 - Face bend test specimen for cladding without a butt weld (FBC).

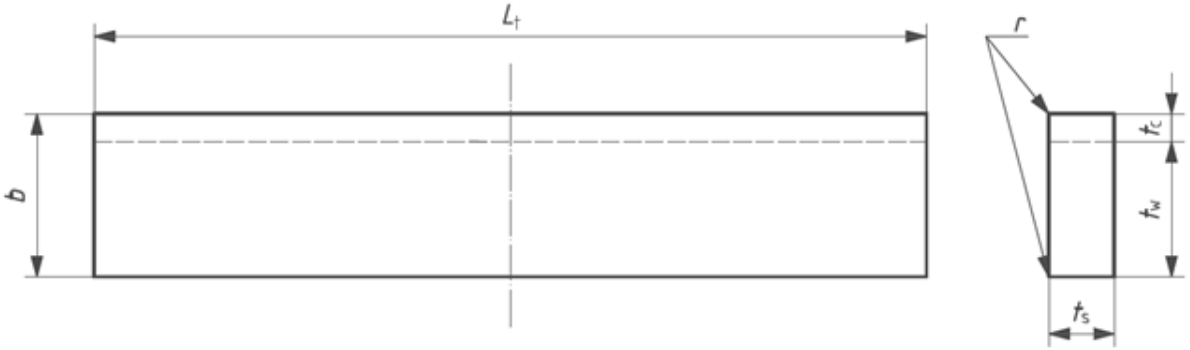


Figure 37 - Side bend test specimen for cladding without a butt weld (SBC).

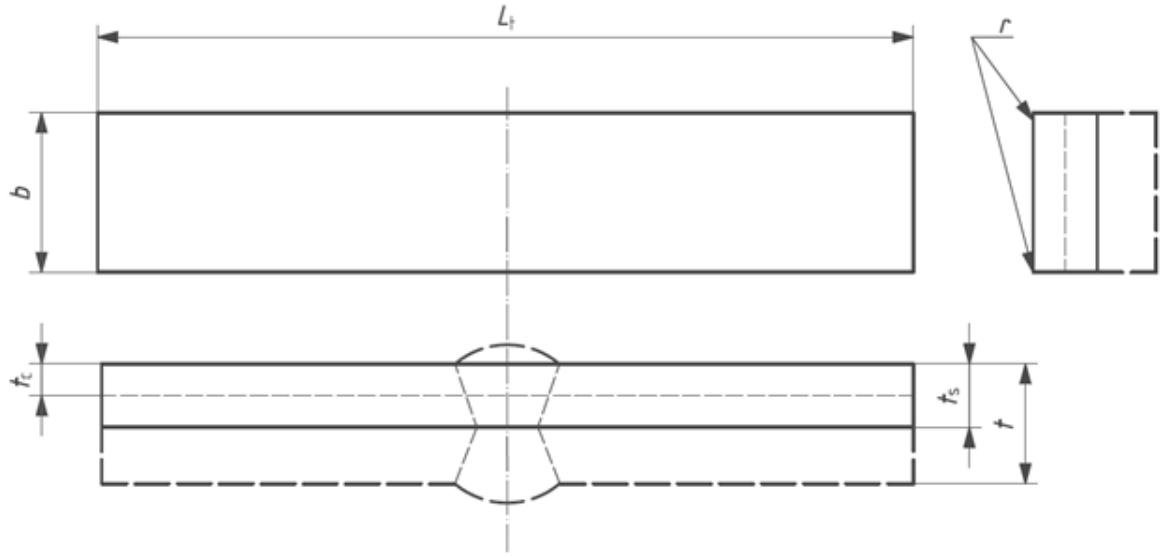


Figure 38 - Face bend test specimen for cladding with a butt weld (FBCB).

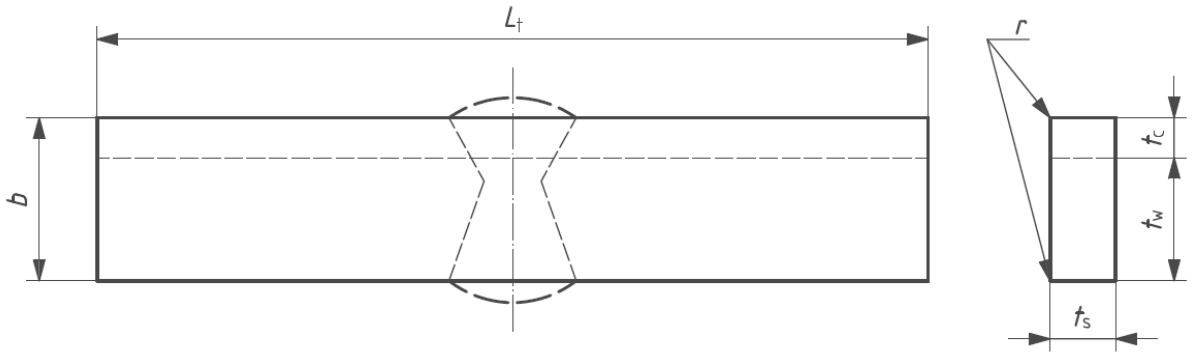


Figure 39 - Side bend test specimen for cladding with a butt weld (SBCB).

2.3.4. Test specimens

Specimens shall be prepared in such a manner that the preparation does not affect either the base material or the weld metal.

For transverse bend testing of butt welds, the test specimen shall be taken transversely from the welded joint of the manufactured product or from the welded test piece in such a way that after machining the weld axis will remain in the centre of the test specimen or at a suitable position for testing. For longitudinal bend testing of butt welds, the test specimen shall be taken longitudinally from the welded joint of the manufactured product or from the welded test piece. The location and orientation of bend test specimens of cladding material shall be specified by the application standard or by agreement between the contracting parties.

Each test piece shall be marked to identify its exact location in the manufactured product or in the joint from which it has been removed. If required by the relevant application standard, the direction of working (e.g. rolling or extrusion) shall be marked. Each test specimen shall be marked to identify its exact location in the test piece from which it has been removed.

No heat treatment shall be applied to the welded joint or to the test specimen unless it is specified or permitted by the relevant application standard dealing with the welded joint to be tested. Details of any heat treatment shall be recorded in the test report. If natural ageing of aluminium alloys takes place, the time between welding and testing shall be recorded.

The mechanical or thermal processes used to extract the test specimen shall not change the properties of the test specimen in any way. It is permissible to mechanically remove any material that is affected by thermal cutting provided the finished dimensions of the specimens as specified in the list reported.

The surfaces of the test specimen shall be machined in such a way that, unless otherwise specified in the relevant application standard and/or by agreement between the contracting parties, all excess weld metal is removed. Unless otherwise specified, the penetration bead may be left intact inside pipes of small diameter on the opposite side of the former. The final stages of preparation shall be obtained by machining or grinding, taking suitable precautions to avoid superficial strain hardening or excessive heating of the material. Within the length l (see Figures 42 to 44), in the Test Procedure paragraph), the surface shall be free from scratches or notches transverse to the test specimen direction, except for undercuts, which shall not be removed unless required by the relevant application standard.

Shearing shall not be used for steel samples with thicknesses > 8 mm. If thermal cutting or other cutting methods which could affect the cut surfaces are used to extract the test specimen from the welded plate, or from the test piece, the cuts shall be made at a distance ≥ 3 mm from the test specimen but, in any case, sufficient (depending on the process used) not to introduce metallurgical effects which could affect the test results.

On other metallic materials, sheared or thermal cut surfaces are not permitted on bend specimens; only machining (e.g. sawing, grinding or milling) shall be used.

In the following list, the specimen size is divided by the type of test:

- **TFBB** and **TRBB** (Transverse root and face bend tests of a butt weld), see Figures 32 and 33
  - t_s = thickness of the base material near the welded joint or t (max 30 mm)
  - if t > 10 mm: t_s may be machined or mechanically finished from one side up to 10 ± 0.5 mm (see Figures 32 and 33)
  - The face or root of the weld shall be in tension when the specimen is bent
  - When t_s > 10 mm is required, several test specimens may be taken in order to cover the full thickness of the joint (see Figure 40); in such cases, the location of the test specimen in the welded joint thickness shall be identified.
  - L_t shall be equal to the required value and shall fulfil the requirements of the appropriate application standards
  - For flat plates: $b \geq 4 \cdot t_s$ unless otherwise specified in the relevant application standard.
  - For pipes with $D \leq 50$ mm: $b = t + 0.1 \cdot D$ (b = 8 mm min)
  - For pipes with D > 50 mm: $b = t + 0.05 \cdot D$ (8 mm < b < 40 mm)
  - For pipes with $D > 25 \cdot wt$, the specimen may be taken as required for the flat plates
  - $r \leq 0.2\ t_s$ (3 mm max), on the face in tension and mechanically machined

- **SBB** (Transverse side bend tests of a butt weld), see Figure 34
  - b = thickness of the base material near the welded joint or t (max 30 mm), see Figure 34
  - required t > 10 ± 0.5 mm unless otherwise specified in the relevant application standard

- When ts > 40 mm it is permissible to split the specimen in the plane of the test piece thickness (see Figure 41); in such cases, the location of the test specimen in the welded joint thickness shall be identified.
- Lt shall be equal to the required value and shall fulfil the requirements of the appropriate application standards
- r ≤ 0.2 ts (3 mm max), on the face in tension and mechanically machined

- **LFBB and LRBB** (Longitudinal bend tests of a butt weld), see Figure 35
  - ts = thickness of the base material near the welded joint or t (max 10 mm)
  - if t > 10 mm: ts may be machined or mechanically finished from one side up to 10 ± 0.5 mm (see Figure 35)
  - The face or root of the weld shall be in tension when the specimen is bent
  - Lt shall be equal to the required value and shall fulfil the requirements of the appropriate application standards
  - b = Ls + 2·b1 (where b1 = 15 mm, unless otherwise specified in the relevant application standard and/or by agreement between the contracting parties.)
  - r ≤ 0.2 ts (3 mm max), on the face in tension and mechanically machined

- **FBC** (Face bend tests of cladding material without a butt weld), see Figure 36
  - ts = tw + tc (max 10 mm)
  - if t > 10 mm: ts may be machined or mechanically finished from the base metal up to 10 ± 0.5 mm (see Figure 36), if cladding thickness permits (otherwise, if tc < 10 mm)
  - if (tw + tc) > 10 mm: it is permissible to remove base material in order to produce a ts in accordance with the application standard or as agreed between the contracting parties.
  - Lt shall be equal to the required value and shall fulfil the requirements of the appropriate application standards
  - For flat plates: b ≥ 4·ts unless otherwise specified in the relevant application standard.
  - For pipes with D ≤ 50 mm: b = t + 0.1·D (b = 8 mm min)
  - For pipes with D > 50 mm: b = t + 0.05·D (8 mm < b < 40 mm)
  - For pipes with D > 25·wt, the specimen may be taken as required for the flat plates
  - r ≤ 0.2 ts (3 mm max), on the face in tension and mechanically machined

- **SBC** (Side bend tests of cladding material without a butt weld), see Figure 37
  - b = tw + tc (max 50 mm)
  - ts = 10 ± 0.5 mm (unless otherwise specified in the relevant application standard)
  - if (tw + tc) > 40 mm: it is permissible to remove base material in order to produce a b in accordance with the application standard or as agreed between the contracting parties.
  - Lt shall be equal to the required value and shall fulfil the requirements of the appropriate application standards
  - r ≤ 0.2 ts (3 mm max), on the face in tension and mechanically machined

- **FBCB** (Transverse face bend tests of cladding material with a butt weld), see Figure 38
  - ts = tw + tc (max 10 mm)
  - if t > 10 mm: ts may be machined or mechanically finished from the opposite side of the cladding (see Figure 38) up to 10 ± 0.5 mm, if cladding thickness permits (otherwise, if tc < 10 mm); in such a case, the location of the weld shall remain in the middle of the test specimen or at a suitable position for testing (see Figure 38)

- When t > ts (in this case: 10 mm max) and when the test concerns the complete joint incorporating both the butt joint and the cladding, several specimens may be taken in order to cover the full thickness of the joint as indicated in Figure 40
- When (tw + tc) > ts (in this case: 10 mm max) and when the purpose of the test is to examine the cladding only, no further tests on the base material are required.
- Lt shall be equal to the required value and shall fulfil the requirements of the appropriate application standards
- For flat plates: b ≥ 4·ts unless otherwise specified in the relevant application standard.
- For pipes with D ≤ 50 mm: b = t + 0.1·D (b = 8 mm min)
- For pipes with D > 50 mm: b = t + 0.05·D (8 mm < b < 40 mm)
- For pipes with D > 25·wt, the specimen may be taken as required for the flat plates
- r ≤ 0.2 ts (3 mm max), on the face in tension and mechanically machined

- **SBCB** (Transverse side bend test specimen for cladding with a butt weld), see Figure 39
  - b = tw + tc (max 50 mm)
  - ts = 10 ± 0.5 mm (unless otherwise specified in the relevant application standard)
  - The location of the weld shall remain in the middle of the test specimen or at a suitable position for testing (see Figure 39)
  - if (tw + tc) > 40 mm: it is permissible to remove base material in order to produce a b in accordance with the application standard or as agreed between the contracting parties.
  - When t > ts (in this case: 10 mm max) and when the test concerns the complete joint incorporating both the butt joint and the cladding, several specimens may be taken in order to cover the full thickness of the joint as indicated in Figure 40
  - When (tw + tc) > ts (in this case: 10 mm max) and when the purpose of the test is to examine the cladding only, no further tests on the base material are required
  - Lt shall be equal to the required value and shall fulfil the requirements of the appropriate application standards
  - r ≤ 0.2 ts (3 mm max), on the face in tension and mechanically machined

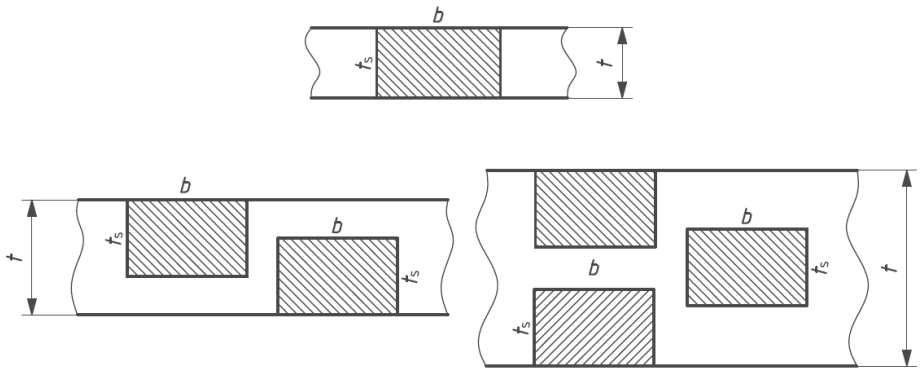


Figure 40: Root and face bend test specimens for a butt weld (TFBB, TRBB, LFBB and LRBB).

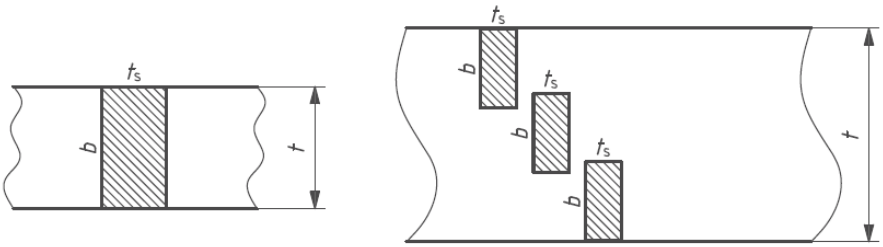


Figure 41: Side bend test specimens for a butt weld (SBB).

2.3.5. Test procedure

There are two main method to conduct a bend test: Testing with a former (see Figures from 42 to 45) and Testing with a roller (Figure 46). Among the methods "testing with a former", there is the U-type jig suggested for thin materials and require a specific jig (see figure 45). The guided bend test with a roller is an alternative method of testing that may be used for aluminium alloys and for joints in other materials where the weld metal, or one of the materials being joined, has a lower yield point or proof strength than the (other) base material.

Before starting the bend test with a former, the shape and the position of the fusion zone or fusion line may be established by lightly macroetching the surface of the test specimen to be tested in tension (see ASTM E340 for further information about the macroetching).

The test with a former shall be carried out by placing the test specimen on two supports consisting of parallel rollers (see Figures 42 to 44) or U-type jig (see Figure 45); the weld shall be at the mid-point between the rollers, except for longitudinal bend tests. The test specimen shall be bent by loading gradually and continuously in the middle of the span, on the axis of the weld, with a load applied by a former (three-point bending) perpendicular to the test specimen surface. The radius of the plunger and die for the U-type jig shall be in accordance with Table 9.

The test with a roller shall be carried out by firmly clamping one end of the test specimen in a testing device having a roller parallel to a former. The test specimen shall be bent by loading, gradually and continuously, by means of the rotation of the outer roller through an arc centred on the axis of the former.

The standard test method ISO 5173 does not specify any testing speed regarding the testing with a former or with a roller; just the recommendation to load the specimen gradually and continuously is required. As general procedure, a total test time around 10÷20 second to perform a bend test is a good starting point to set the testing speed accordingly.

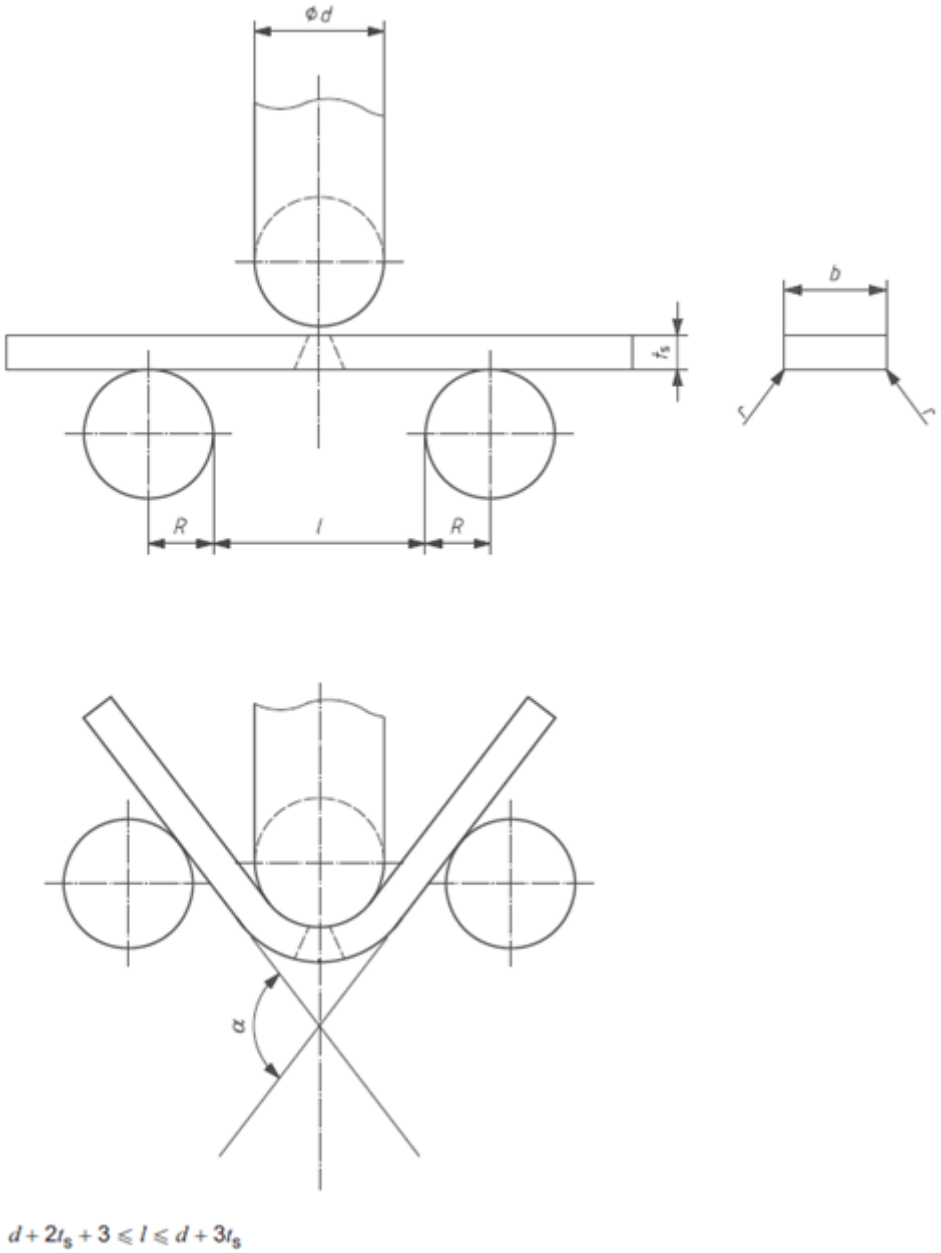
The distance between the rollers is reported in Figures 42 to 44, whereas the diameter of the former and roller is related to the elongation (A) of the parent metal of the specimens, determined through the tensile test (see ISO 6892-1). In particular, two cases are distinguished: materials with A < 20% and materials with A ≥ 20% as shown in Table 10.

The test is completed when the test reaches the definition of test completion given in the relevant application standard (e.g. a specific bending angle is reached). Otherwise the following definitions may be applied on the basis of the type of the conducted test (with a former, with jig, with roller):

- Figures 42 to 44: specimen is ejected from the bottom of the fixture;
- Figure 45: a 3 mm wire cannot be inserted between the specimen and the lower fixture;
- Figure 46: the outer roller has been moved 180° from the starting point.
- 6.6 Bending elongation

The bend test allows to quantify ductility of the specimen by the measuring of the elongation; in such case, if this result is required, the root or face bend test specimens of steel shall have a gauge length in accordance with the following conditions:

- Fusion welds: $L_0 = L_s$ or $L_0 = 2 \cdot L_s$ or $L_0 = L_s - t_s$
- Pressure welds, electron beam welds and laser welds: $L_0 = t_s$ or $L_0 = 2 \cdot t_s$



$$d + 2t_s + 3 \leqslant l \leqslant d + 3t_s$$

Figure 42 - Transverse face or root bend test.

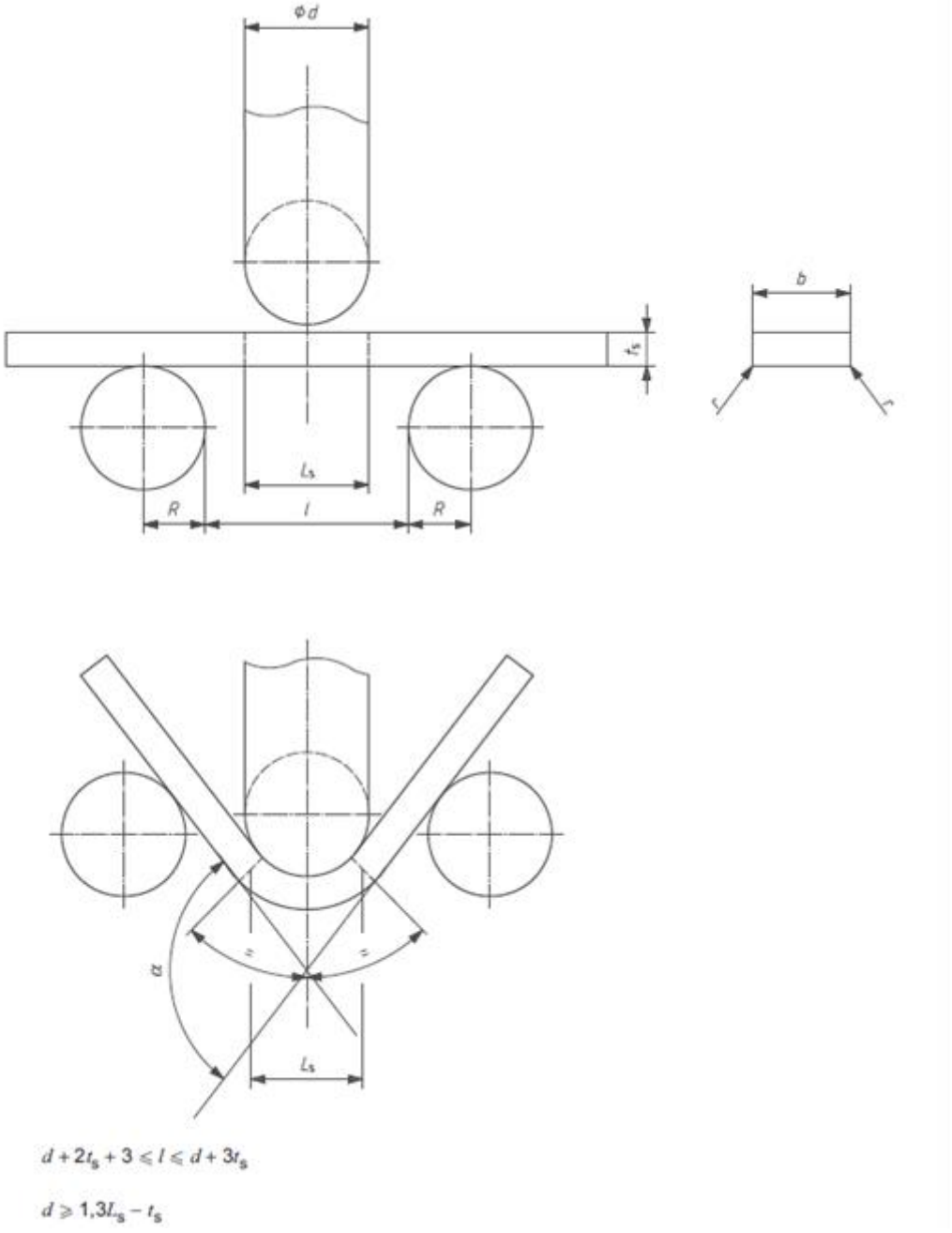


Figure 43 - Transverse side bend test.

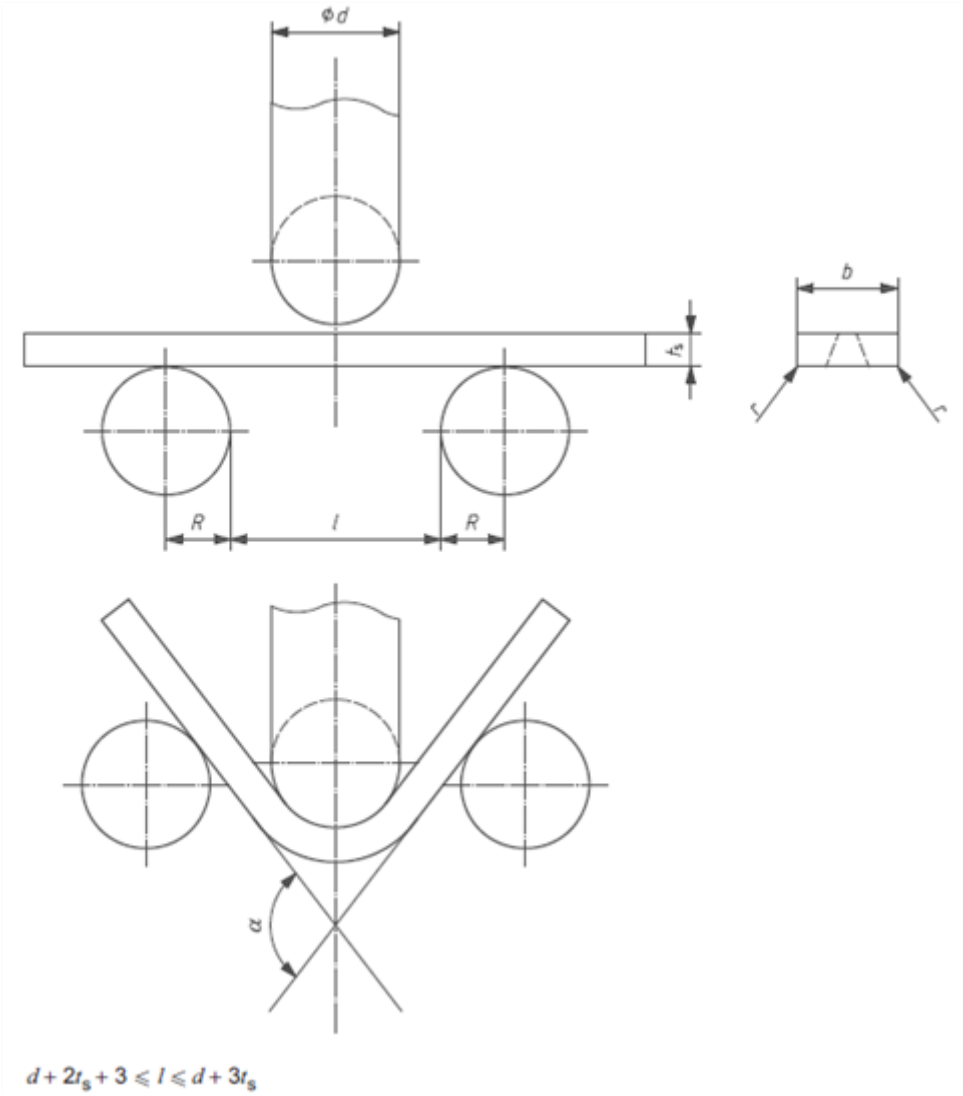
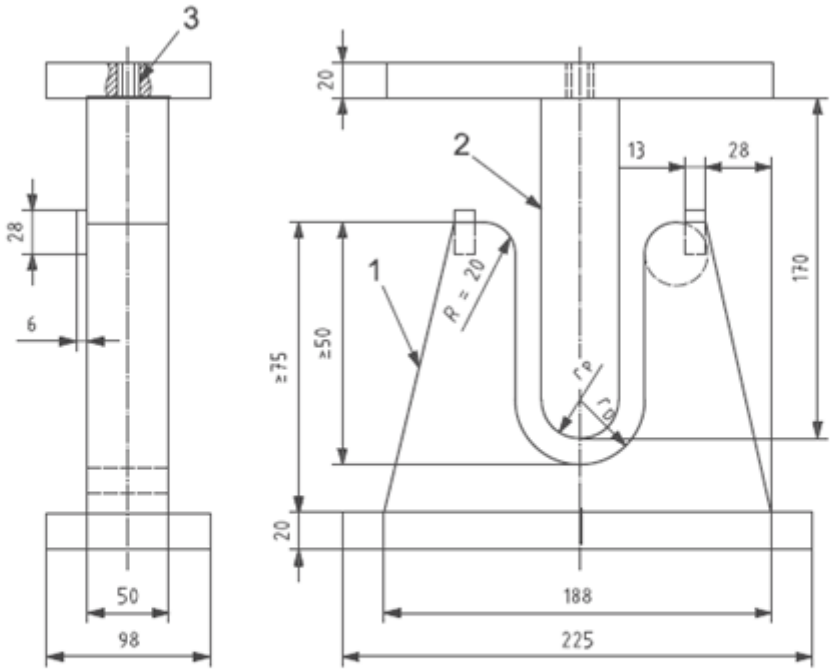


Figure 44 - Longitudinal bend test.

Dimensions in millimetres



Key

r_P plunger radius
r_D die radius
1 die
2 plunger
3 tapped hole for attaching plunger to test machine

Figure 45 - Example of shape of U-type jig for bend test of thin specimens.

Specimen thickness [mm]	**Plunger radius** [mm]	**Die radius** [mm]
10	20	32
t_s	$2 \cdot t_s$	$r_p + t_s + 2$

Table 9 - Fixture dimensions — U-type jig.

Dimensions in millimetres

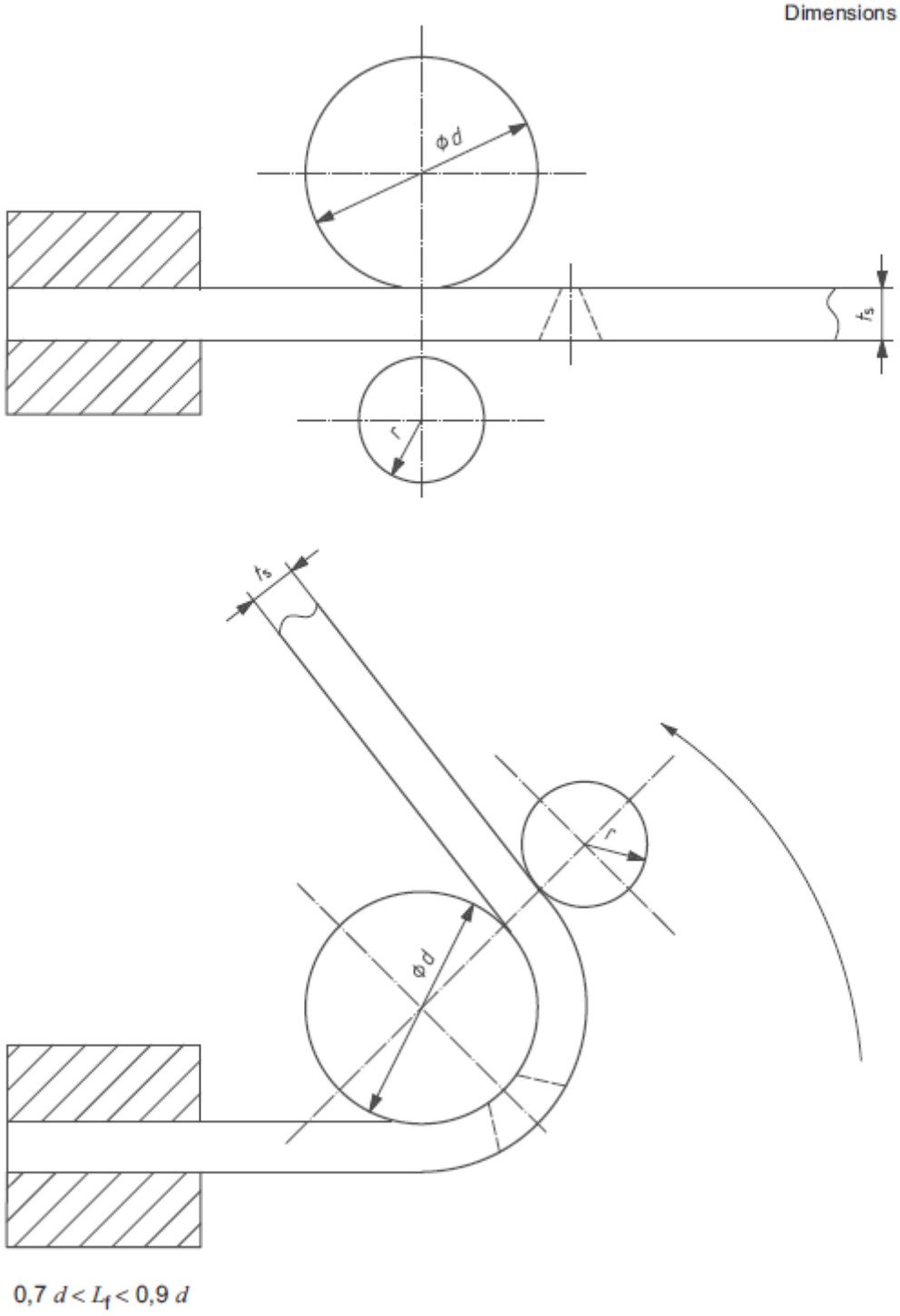


Figure 46 - Method of bend testing using a roller.

Elongation of parent metal, **A** [%]	**Diameter of the former or the inner roller,** **d** [mm]

≥ 20	$4 \cdot t_s$
< 20	$100 \cdot t_s A - t_s$

Table 10 - Diameter of former and roller.

2.3.6. Test result

After bending, both the external surface and the sides of the test specimen shall be examined. The evaluation of the bend test specimen shall be made and reported in accordance with the relevant application standard (e.g. if ISO 15614-1 is applied, during the testing, the test specimens shall not reveal any imperfection > 3 mm in any direction; imperfections appearing at the corners of a test specimens during testing shall be ignored in the evaluation).

2.3.7. Test report

If ISO 5173 is applied, the test report shall include at least the following information:

- reference to the applied standard test method with the year of publication, i.e. ISO 5173;
- identification of the test specimen (marking, type of base material, heat treatment, etc.);
- shape and dimensions of the test specimen;
- type and symbol of bend test (root and face, transverse or longitudinal, side transverse bend test);
- conditions of testing (see the paragraph “Test procedure”):
- test methods (former or roller);
- diameter of the former;
- distance between rollers.
- testing temperature if not in the temperature range (23 ± 5) °C;
- type and dimensions of imperfections observed;
- bending angle.
- elongation (if required)
- An example of a typical test report is given in Example 1.

2.3.8. Example 1

An example of a typical test report, see Figure 27.

Example of a test report

N° .....

According to pWPS .....

According to test result "bend test"

test result "..... "

Manufacturer: .....

Purpose of the examination: .....

Form of product: .....

Base material: .....

Consumable: .....

Test temperature: .....

Table A.1 — Bend test in accordance with ISO 5173

Specimen N°/position	Type of test	Dimensions mm	Former diameter mm	Distance between rollers mm	Bend angle °	Original gauge length mm	Elongation %	Remark e.g. fracture appearance

Examiner or examining body: Approved by:

....

(name, date and signature) (name, date and signature)

Figure 47 - Example of a test report according to ISO 9017.

2.3.9. Example 2

Some pictures related to the different step of a bend test are reported in the following figures, see Figure 48.

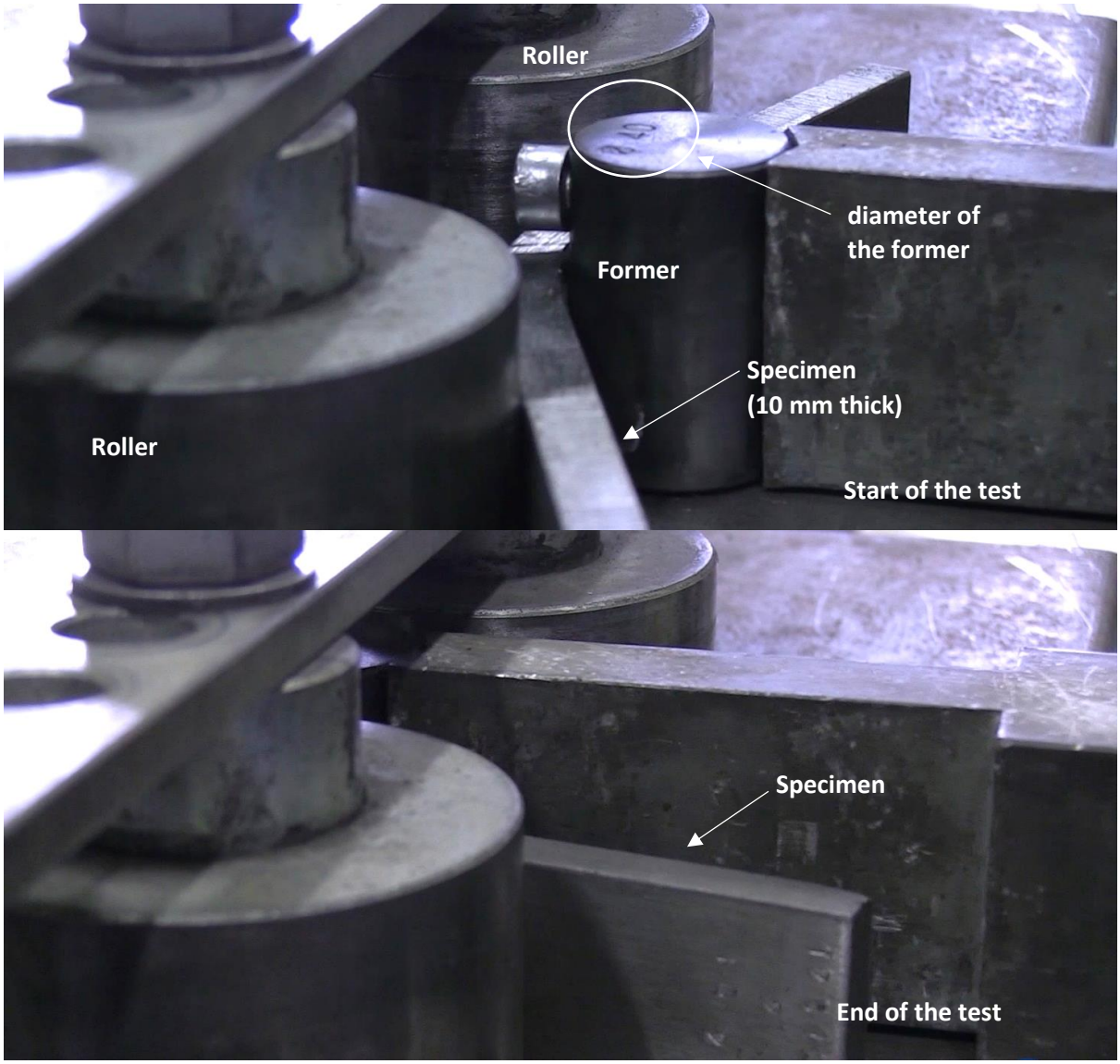


Figure 48 - Images of bend test: start (on the top) and end (on the bottom).

2.3.10. Example 3

In the pictures below, two specimens are reported: a specimen with no imperfection after the test (acceptable results according to ISO 15614-1) and a failed specimen (not acceptable results according to ISO 15614-1), see Figure 49.

Figure 49 - Images of acceptable result (no imperfections after the test, see top image) and not acceptable result (failed specimen: bottom image) according to ISO 15614-1.

2.4. Charpy Impact Strength Test of Metals and Welded Joints

2.4.1. Foreword

The Impact test is related to a test where the specimen is ruptured instantaneously through the dynamic load caused by the impact of a falling weight; in this chapter the use of a Charpy pendulum to break different kind of specimens will be introduced and discussed. In particular, the main reference of this chapter is ISO 148 which is focused on V-notch and U-notch specimens and describe the method to determine determining the energy absorbed in an impact test of metallic materials.

2.4.2. References

- ISO 148-1 Metallic materials - Charpy pendulum impact test - Part 1: Test method
- ISO 148-2 Metallic materials - Charpy pendulum impact test - Part 2: Verification of testing machines
- ISO 148-3 Metallic materials - Charpy pendulum impact test - Part 3: Preparation and characterization of Charpy V-notch test pieces for indirect verification of pendulum impact ma chines
- ISO 9016 - Destructive tests on welds in metallic materials - Impact tests - Test specimen location, notch orientation and examination
- SEP 1670 Determination of brittle-ductile transition temperature FATT and other characteristic properties
- ISO 286-1 Geometrical product specifications (GPS) — ISO code system for tolerances on linear sizes — Part 1: Basis of tolerances, deviations and fits

2.4.3. Introduction

The scope of the impact test is to determine the impact toughness of a material or a weld through the measurement of the energy spent to rupture a notched specimen. Such result can be related to the temperature at which the specimen is tested, indeed, metallic materials highlight a specific behaviour with respect to the testing temperature and depending on the type of materials (e.g. ferritic steels) a transition curve of the toughness or vs. the temperature can be observed.
The Charpy impact test consists of breaking a notched test piece with a single blow from a swinging pendulum; the notch in the test piece has a specified geometry and is located in the middle between two supports, opposite to the location which is impacted in the test. The energy absorbed in the impact test, the lateral expansion and the shear fracture appearance are normally determined.
Because the impact values of many metallic materials vary with temperature, tests shall be carried out at a specified temperature. When this temperature is other than ambient, the test piece shall be heated or cooled to that temperature, under controlled conditions. Through these results curves to observe the behaviour of a material vs. temperature can be drawn; different methods are available to fit the experimental data points, therefore, in this chapter, the technique suggested by SEP 1670 will be examined and described.
Furthermore, the position and the orientation where a specimen is taken is very important and have to be specified in the test report to proper relate the result to the specific position of the specimen. Moreover, the position of the notch is important, in the case of a weld, the notch can be placed in the close to the fusion line, on the weld metal or in the heat affected zone; therefore, the results obtained from the same weld will vary depending on the position of the notch. The standard ISO 9016 helps to identity the position where a specimen is taken and where the notch is placed as regards to the weld.
The Charpy pendulum impact test is often used in routine, high-throughput pass/fail acceptance tests in industrial settings. For these tests, it may not be important whether the test sample is completely

broken, partially broken, or simply plastically deformed and dragged through the anvils. In research, design, or academic settings, the measured energy values are studied in more detail, in which case it can be highly relevant whether the sample is broken or not.
It is important to note that not all Charpy pendulum impact test results can be directly compared. For example, the test can be performed with hammers having strikers with different radii, or with different test piece shapes. Tests performed with different strikers can give different results, and test results obtained with differently shaped test pieces can as well. This is why not only the adherence to ISO 148 but also a clear and complete reporting of the type of instrument, the test piece and the details of the post-test test pieces are crucial for comparability of results.
In the following table, the list of terms adopted in ISO I48-1 are reported together with their descriptions and the unit (see Table 11).
In Figure 50 a sketch of a Charpy pendulum is reported with the picture of a pendulum in a lab whereas in Figure 51 the test piece terminology showing configuration of test piece supports and anvils of a pendulum impact-testing machine.

Term	Unit	Description
W	mm	thickness of test piece
h	mm	width of test piece
l	mm	length of test piece
α	°	angle of fall of the pendulum
$ß_1$	J or °	angle of rise when the machine is operated in the normal manner without â test piece in position
$ß_2$	J or °	angle of rise when the machine is operated in the normal manner without a test piece in position and without resetting the indication mechanism
LE	mm	lateral expansion
K	J or °	absorbed energy (expressed as KV_2, KV_8, KU_2, KU_8, to identify specific notch geometries and the radius of the striking edge)
K_1	J or °	indicated absorbed energy when the machine is operated in the normal manner without a test piece in position
K_2	J or °	indicated absorbed energy when the machine is operated in the normal manner without a test piece in position and without resetting the indication mechanism
K_N	J	nominal initial potential energy (energy assigned by the manufacturer of the pendulum impact testing machine)
K_p	J	initial potential energy (potential energy)
KV_2	J	absorbed energy for a V-notch test piece using a 2 mm striker
KV_8	J	absorbed energy for a V-notch test piece using a 8 mm striker
KU_2	J	absorbed energy for a U-notch test piece using a 2 mm striker
KU_8	J	absorbed energy for a U-notch test piece using a 8 mm striker
F	N	Force related to the weight of the falling weight (hammer
l_2	N	Length of the harm at which the falling weight is connected
M	N·m	Moment equal to the product $F \cdot l_2$
p	J	absorbed energy loss caused by pointer friction
p'	J	absorbed energy loss caused by bearing friction and air resistance
$p_ß$	J	correction of absorbed energy losses for an angle of rise *ß*
SFA	%	shear fracture appearance

Tj	°C	transition temperature
T_{t27}	°C	transition temperature defined at a specific value of absorbed energy; for example, Z7 J
$T_{t50\ \%US}$	°C	transition temperature defined at a particular percentage of the absorbed energy of the upper shelf; for example, 50 %
$T_{t50\ \%SFA}$	°C	transition temperature defined at a particular proportion of shear fracture; for example, 50 %
$T_{t0,9}$	°C	transition temperature defined at a particular amount of lateral expansion; for example, 0,9 mm

Table 11 - List of terms and definitions taken from ISO 148-1.

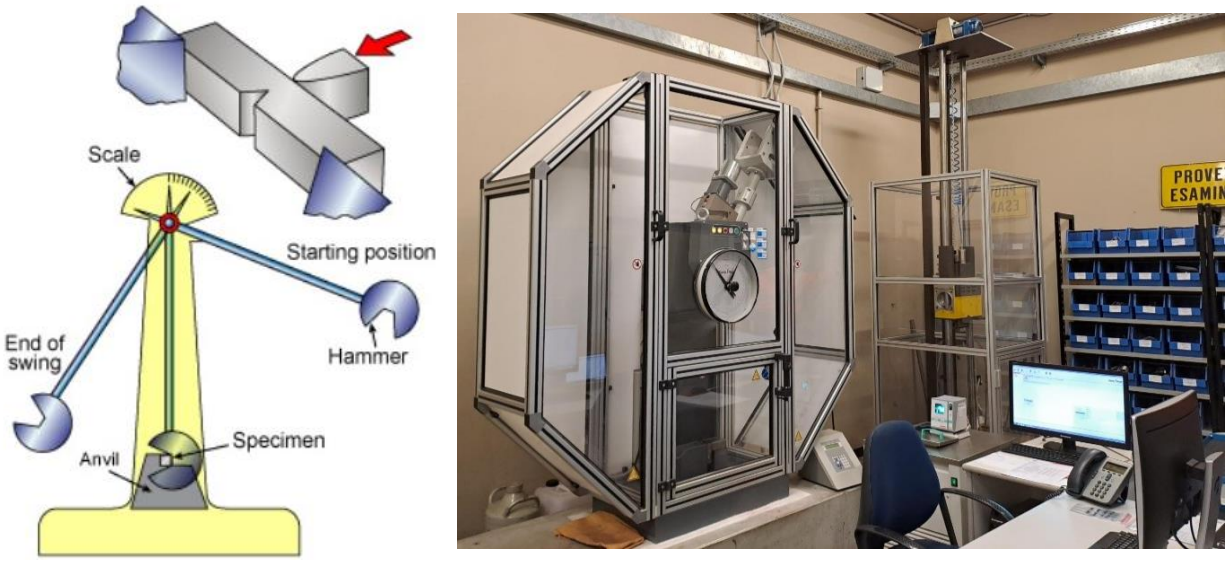
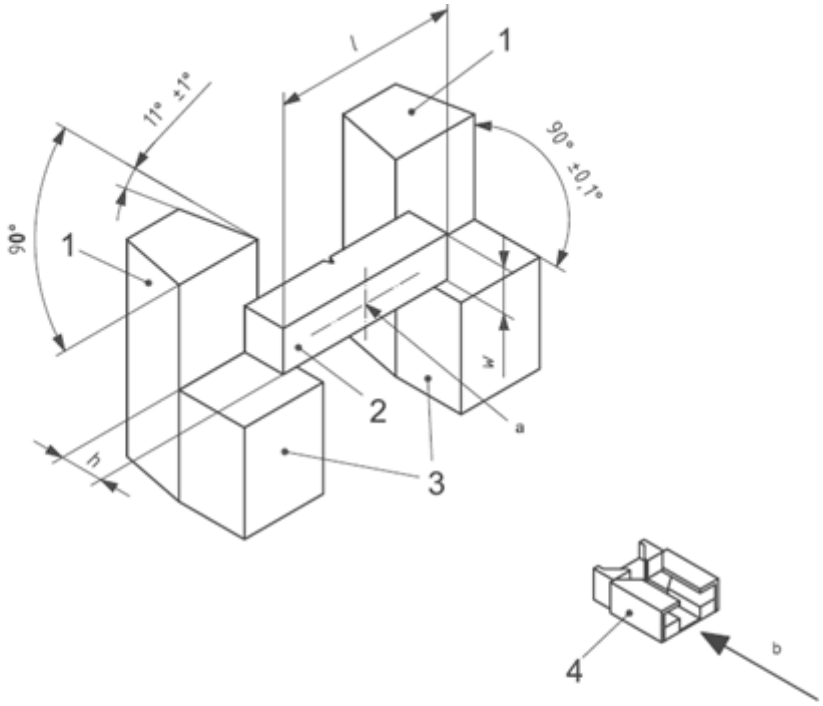


Figure 50 - Sketch of a Charpy pendulum (on the left) and picture of a pendulum in a lab (on the right, courtesy of IIS).



Key

1 anvil
2 standard-sized test piece
3 test piece supports
4 shroud

h height of test piece
l length of test piece
w width of test piece
a Centre of strike.
b Direction of pendulum swing.

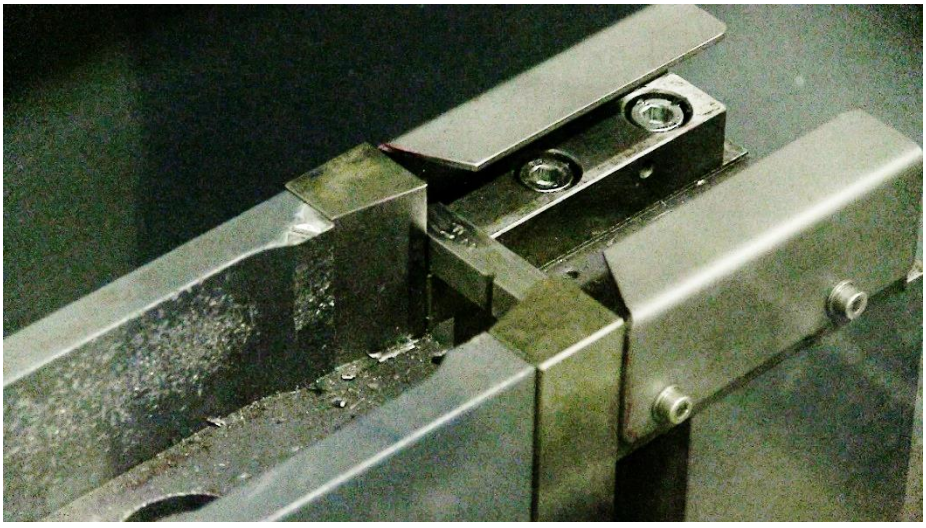


Figure 51 - On the top: Test piece terminology showing configuration of test piece supports and anvils of a pendulum impact-testing machine; on the bottom: picture of the supporting anvils with mounted test piece before the impact with the hammer (the white arrow indicates the direction and the side of the impact on the test piece).

2.4.4. Test specimens

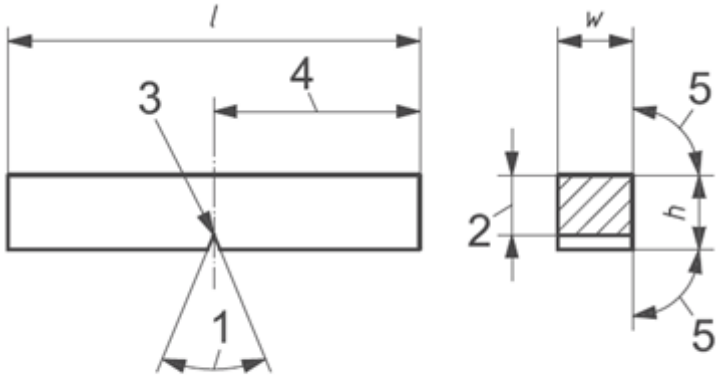
The standard test piece for the impact test according to ISO 148-1 is 55 mm long and of 10 x 10 mm square section: in the centre of the length, there shall be either a V-notch or a U-notch. The V-notch shall have an included angle of 45°, a depth of 2 mm and a root radius of 0,25 mm while the U-notch shall have a depth of 5 mm (unless otherwise specified) and a root radius of 1 mm (see Figure 52 and Table 12). In Figure 53 the measurement of the root radius on a V-notch is performed through the software of an optical microscope.

If the standard test piece cannot be obtained from the material, one of the subsize test pieces, having a thickness of 7,5 mm, 5 mm or 2,5 mm (see Figure 51 and Table 12), shall be used, if not otherwise specified. Note direct comparison of results is only of significance when made between test pieces of the same form and dimensions. Furthermore, for low energies, the use of shims to better position subsize test pieces relative to the centre of strike is important to avoid excess energy absorption by the pendulum. For high energies, this might not be as important. Shims can be placed on or under the test piece supports, with the result that the mid-thickness of the specimen is 5 mm above the 10 mm supports. Shims can be temporarily fixed to the supports using tape or another means.

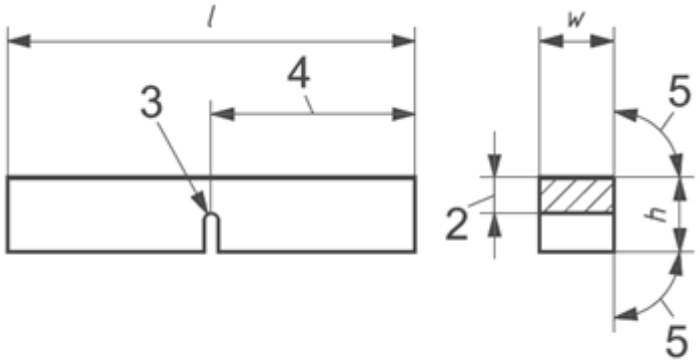
When a heat-treated material is being evaluated, the test piece shall be finish-machined and notched after the final heat treatment, unless it can be demonstrated that machining before heat treatment does not affect test results.

The preparation shall be executed in such a way that any alteration of the test piece, for example due to heating or cold working, is minimized; the test piece may be marked on any face not in contact with supports, anvils or striker and at a position where plastic deformation and surface discontinuities caused by marking do not affect the absorbed energy.

The test piece can be machined from a base material (e.g. a plate or a piece) or from a weld; in this last case, the standard ISO 9016 shall be applied to correctly identify the location where the test pieces are extracted from the weld and the exact position of the notch with reference to the heat affected zone, the weld metal, the cap or the root of the weld.



a) V-notch geometry



b) U-notch geometry

Figure 52 - Charpy pendulum impact test piece; For the symbols L, W, B and the numbers 1 to 5, see Table 12.

Designation	Symbol and no.	V-notch test piece			U-notch test piece		
		Nominal dimension	Machining tolerance	Tolerance class[a]	Nominal dimension	Machining tolerance	Tolerance class[a]
Length	*l*	55 mm	± 0,60 mm	js15	55 mm	± 0,60 mm	js15
Width	*h*	10 mm	± 0,075 mm	js12	10 mm	± 0,11 mm	js13
Thickness[c] • *standard test piece* • *subsize test piece* • *subsize test piece* • *subsize test piece*	*W*	 10 mm 7,5 mm 5 mm 2,5 mm	 ± 0,11 mm ± 0,11 mm ± 0,06 mm ± 0,05 mm	 js13 js13 js12 js12	 10 mm 7,5 mm 5 mm ---	 ± 0,11 mm ± 0,11 mm ± 0,06 mm ---	 js13 --- --- ---
Angle of notch	*1*	45°	± 2°	---	---	---	---
Ligament	*2*	8 mm	± 0,075 mm	js12	5 mm	± 0,09 mm	js13
Notch radius	*3*	0,25 mm	± 0,025 mm	---	1 mm	± 0,07 mm	js12
Notch position (centering)	*4*	27,5 mm	± 0,42 mm[d]	js15	27,5 mm	± 0,42 mm[d]	js15
Angle between plane of symmetry of notch and longitudinal axis of test piece		90°	± 2°	---	90°	± 2°	---
Angle between adjacent longitudinal faces of test piece	*5*	90°	± 2°	---	90°	± 2°	---
Surface roughness[b]	NA	< 5 µm	---	---	< 5 µm	---	---

[a] In accordance with ISO 286-1,
[b] The test pieces shall have a surface roughness better than Ra 5 ¡rm except for the ends,

[c] If another thickness (2 mm or 3 mm) is specified, the corresponding tolerances shall also be specified.
[d] For machines with automatic positioning of the test piece, it is recommended that the tolerance be taken as ± 0,165 mm instead of ± 0,42 mm,

Table 12 - Tolerances on specified test piece dimensions.

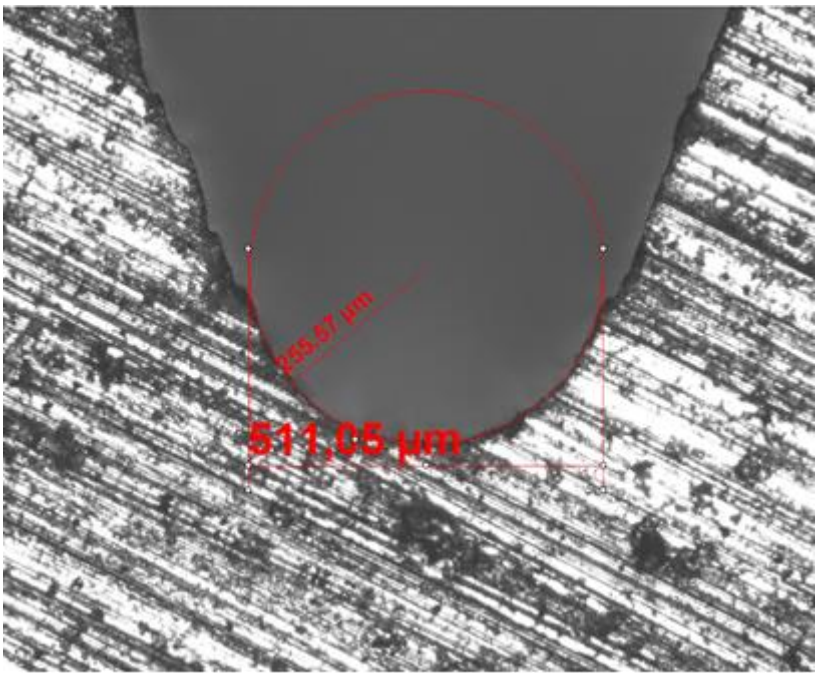


Figure 53 - Verification of the notch radius using an optical microscope.

2.4.5. Test procedure

The measurements of the instrument and test piece details shall be traceable to national or international standards. Equipment used for measurements shall be calibrated within suitable intervals (the testing machine shall be installed and verified in accordance with ISO 148-2).

The striker geometry shall be specified as being either the 2 mm striker or the 8 mm striker. It is recommended that the radius on the striker be shown as a subscript as follows: KV_2 or KV_8 and KU_2 or KU_8. Reference shall be made to the product specification for striker geometry guidance (Note tests carried out with 2 mm and 8 mm strikers can give different results, see ISO 148-1).

Unless otherwise specified, tests shall be carried out at 23 °C ± 5 °C (room temperature); if a temperature is specified, the test piece shall be conditioned to a temperature within ± 2 °C. For conditioning (heating or cooling) using a liquid medium, the test piece shall be positioned in a container on a grid that is at least 25 mm above the bottom of the container and covered by at least 25 mm of liquid, and be at least 10 mm from the sides of the container; the medium shall be constantly agitated and

brought to the specified temperature by any convenient method. The device used to measure the temperature of the medium should be placed in the centre of the group of test pieces and the temperature of the medium shall be held at the specified temperature within ± 1 °C for at least 5 min (if the difference between the temperature of the specimen and the testing temperature is greater than 40°C (e.g. test piece to be cooled from room temperature to -40°C); it is suggested to wait at least 10÷15 minutes to be sure the test pieces are uniformly conditioned along the thickness).

When a liquid medium is near its boiling point, evaporative cooling can dramatically lower the temperature of the test piece during the interval between removal from the liquid and fracture. For conditioning (heating or cooling) using a gaseous medium, the test piece shall be positioned in a chamber at least 50 mm from the nearest surface. Individual test pieces shall be separated by at least 10 mm. The medium shall be constantly circulated and brought to the specified temperature by any convenient method; the device used to measure the temperature of the medium should be placed in the centre of the group of test pieces, the temperature of the gaseous medium shall be held at the specified temperature within ± 1 °C for at least 30 min before the test piece is removed from the medium for testing.

Other methods for heating or cooling are allowed, if the other pertinent requirements (above cited) are fulfilled.

When testing is performed at other than room temperature, not more than 5 s shall elapse between the time the test piece is removed from the heating or cooling medium and the time it is impacted by the striker. An exception is made if the difference between the ambient or instrument temperature and the test piece temperature is less than 25 °C in which case the time for specimen transfer shall be less than 10 s. The transfer device shall be designed and used in such a way that the temperature of the test piece is maintained within the permitted temperature range. The parts of the device in contact with the specimen during transfer from the medium to the machine shall be conditioned with the specimens.

Care should be taken to ensure that the device used to centre the test piece on the anvils does not cause the fractured ends of low-energy, high-strength test pieces to rebound of the device into the pendulum. This pendulum/test piece interaction results in erroneously high indicated energy. It has been shown that clearance between the end of a test piece in the test position and the centring device,

or a fixed portion of the machine, shall be equal to or greater than 13 mm to avoid the ends of the test pieces rebounding into the pendulum during the test.

Self-centring tongs, similar to those shown in Figure 54 for V-notched test pieces, are often used to transfer the test piece from the temperature-conditioning medium to the proper test positions; tongs of this nature eliminate potential clearance problems due to interference between the fractured specimen halves and a fixed centring device.

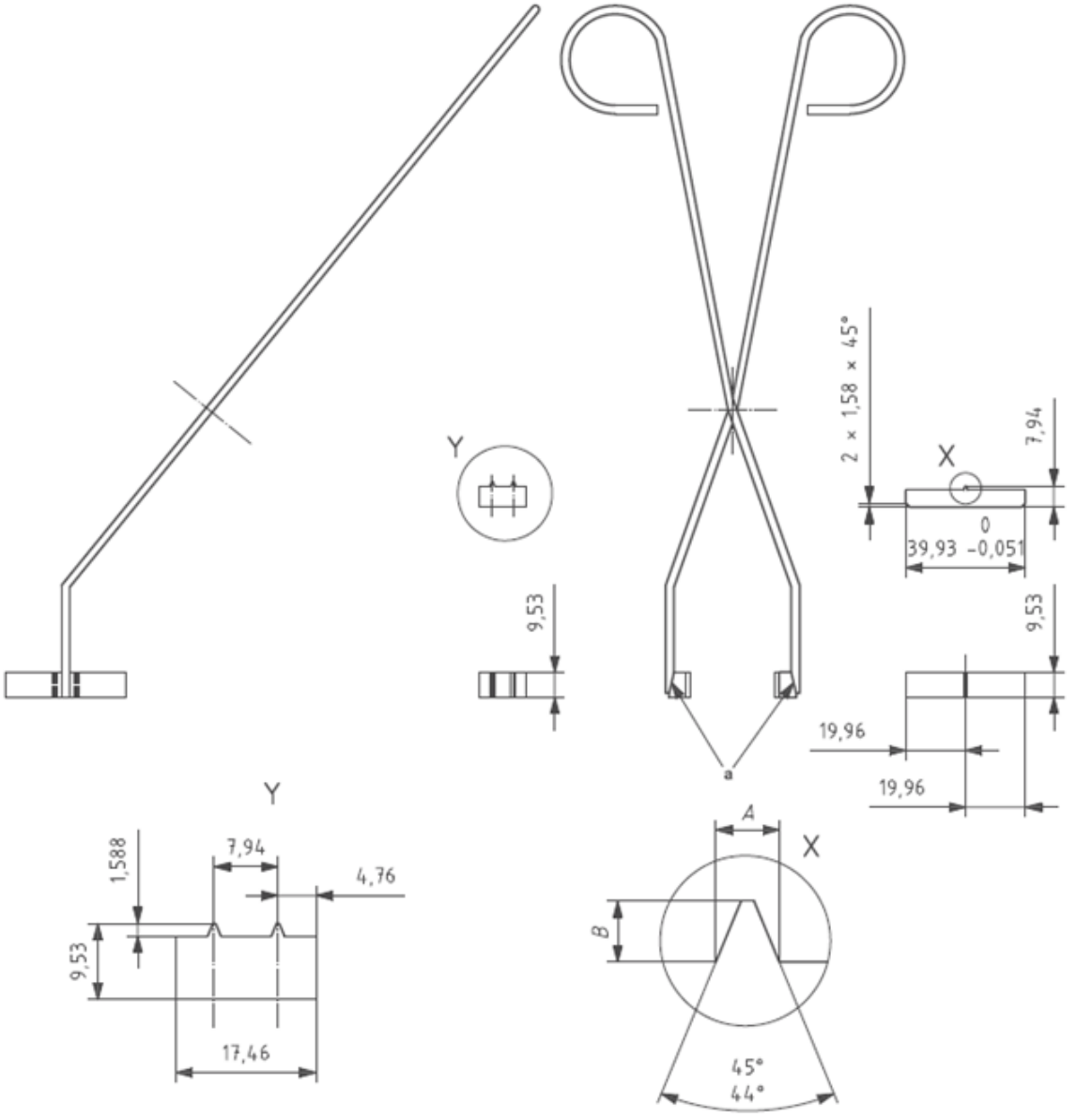
The absorbed energy, K, should not exceed 80 % of the initial potential energy, K_p. If the absorbed energy exceeds this value, the absorbed energy shall be reported as approximate, and it shall be noted in the test report as exceeding 80 % of the machine capacity. Ideally, an impact test would be conducted at a constant impact velocity. In a pendulum-type test, the velocity decreases as the fracture progresses. For specimens with impact energies approaching the capacity of the pendulum, the velocity of the pendulum decreases during fracture to the point that accurate impact energies are no longer obtained.

Test pieces do not always break into two pieces during the test; for material acceptance testing, it is not required to report information concerning incomplete fracture. For tests, other than material acceptance testing, it is required that unbroken test pieces are reported.

In the case where individual specimens are not identified within test records, the group can be identified as broken or unbroken. A test piece that is not fully separated in two half test pieces upon impact can be considered broken if the two halves can be separated by pushing the hinged halves together without the aid of mechanical tools and without fatiguing the specimen. A material acceptance test is a test which is used to assess a minimum acceptance requirement.

If a test piece jams in the machine, the results shall be disregarded, and the machine thoroughly checked for damage that would affect its state of calibration. Note jamming occurs when a broken test piece is caught between moving and non-moving parts of the testing machine. It can result in significant energy absorption. Jamming can be differentiated from secondary strike marks, because jamming is associated with a pair of opposing marks on the specimen.

Dimensions in millimetres



Specimen width	Base width *A*	Height *B*
10	1,60 to 1,70	1,52 to 1,65
5	0,74 to 0,80	0,69 to 0,81
3	0,45 to 0,51	0,36 to 0,48

a Steel pieces silver-soldered to tongs parallel to each other.

Figure 54 - Centring tongs for V-notched Charpy specimens.

2.4.6. Test result

If post-fracture inspection shows that any portion of the test specimen identification marking is in a portion of the test piece which is visibly deformed, the test result might not be representative of the material and this shall be noted in the test report.

A measure of the ability of the material to resist fracture when subjected to triaxial stresses, such as those at the root of the notch in a Charpy test piece, is the amount of deformation that occurs at this location (in this case: contraction). Because of the difficulties in measuring this deformation, even after fracture, the expansion that occurs at the opposite end of the fracture plane is customarily measured and used as a proxy for the contraction.

The method of measuring lateral expansion (LE) should consider the fact that the fracture plane seldom bisects the point of maximum expansion on both sides of a test piece. One half of a broken test piece might include the maximum expansion for both sides, one side only, or neither; the techniques used should therefore provide an expansion value, equal to the sum of the higher of the two values obtained for each side, by measuring the two halves separately. The amount of expansion on each side of each half shall be measured relative to the plane defined by the undeformed portion of the side of the test piece (see Figure 57). Contact and non-contact methods can be used for these measurements. Lateral expansion may be measured by using a gauge similar to that shown in Figures 55 and 56; measure the two broken halves individually. First, however, check the sides perpendicular to the notch to ensure that no burrs were formed on these sides during Impact testing; if such burrs exist, they shall be removed, for example by rubbing with an emery cloth, making sure that the protrusions to be measured are not rubbed during the removal of the burr. Next, place the half-specimens together so that the surfaces originally opposite the notch are facing one another. Take one of the half-specimens (see Figure 55) and press it firmly against the reference supports, with the protrusions against the gauge anvil. Note the reading, and then repeat this step with the other half-specimen (see Figure 55), ensuring that the same side is measured; the larger of the two values is the expansion of that side of the broken test piece. Repeat this procedure to measure the protrusions on the opposite side, and then add the larger values obtained for each side. For example, if $A_1 > A_2$ and $A_3 = A_4$, consequently LE = A_1 + (A_3 or A_4). If $A_1 > A_2$ and $A_3 > A_4$, consequently, LE = $A_1 + A_3$. If one or more protrusions of a test piece have been damaged by contacting the anvil, machine mounting surface, etc., the test piece shall not be measured and the conditions shall be indicated in the test report.

The fracture surface of Charpy test pieces is often rated by the percentage of shear fracture which occurs. The greater the percentage of shear fracture, the greater the notch toughness of the material. The fracture surface of most Charpy specimens exhibits a mixture of shear and flat fracture regions. The shear regions are assumed to be fully ductile, but the flat fracture regions can be ductile, brittle, or a combination of these fracture modes. Because the rating is extremely subjective, it is recommended that it is not to be used in specifications. NOTE The term fibrous-fracture appearance is often used as a synonym for shear fracture appearance. The terms cleavage fracture appearance and crystallinity are often used to express the opposite of shear fracture.

The percentage of shear fracture is commonly determined by any one of the following methods:

A. measuring the length and width of the cleavage portion (the "shiny" portion) of the flat fracture region, as given in Figure 57, and determining the percent shear from Table 13;
B. comparing the appearance of the fracture of the test piece with a fracture appearance chart, such as that given in Figure 58 and 59;
C. magnifying the fracture surface and comparing it to a recalibrated overlay chart, or measuring the per cent cleavage fracture by means of a planimeter, then calculating per cent shear fracture (as 100 % cleavage fracture;
D. photographing the fracture surface at a suitable magnification and measuring the per cent cleavage fracture by means of a planimeter, then calculating per cent shear fracture (as 100 % cleavage fracture);
E. measuring the per cent shear fracture by image analysis techniques.

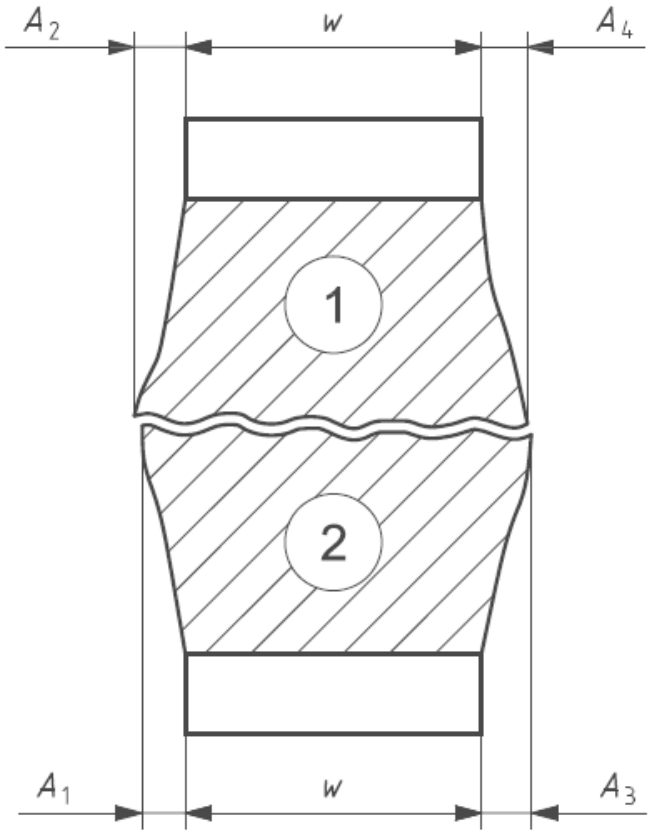


Figure 55 - Halves of broken Charpy V-notched impact specimen, illustrating the measurement of lateral expansion, dimensions A_1, A_2, A_3, A_4 and the original width, dimension W. Note the halves are numbered 1 and 2.

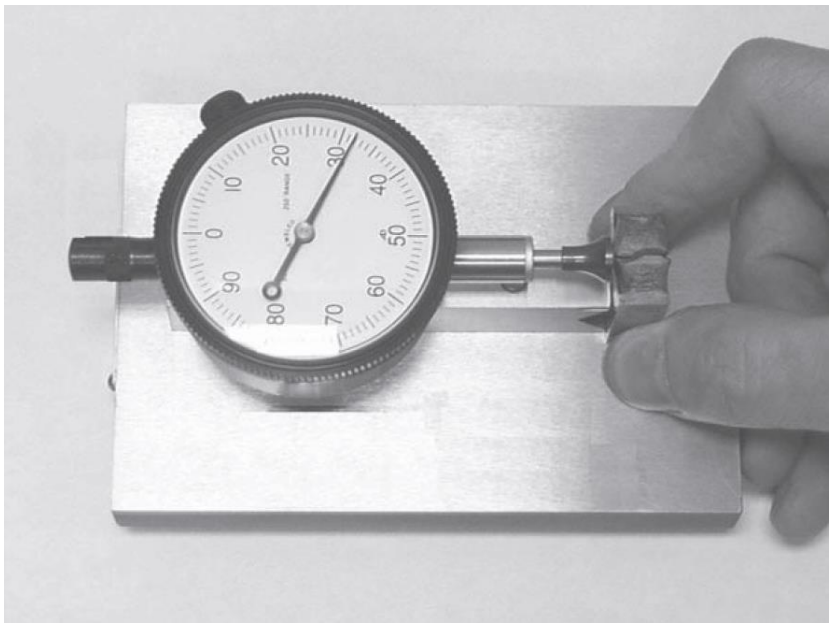
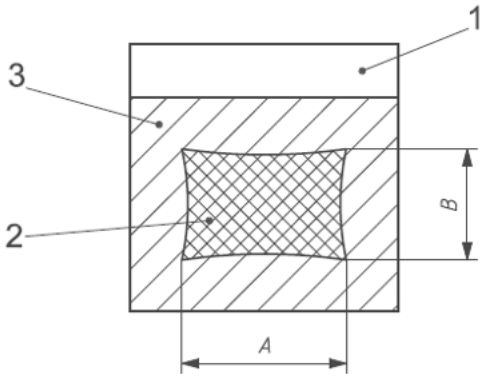


Figure 56 - Lateral expansion gauge for Charpy specimens (for the assembly and the details of the gauge, see ISO 148-1).



Key

1 notch
2 cleavage area (brittle)
3 shear area (dull)

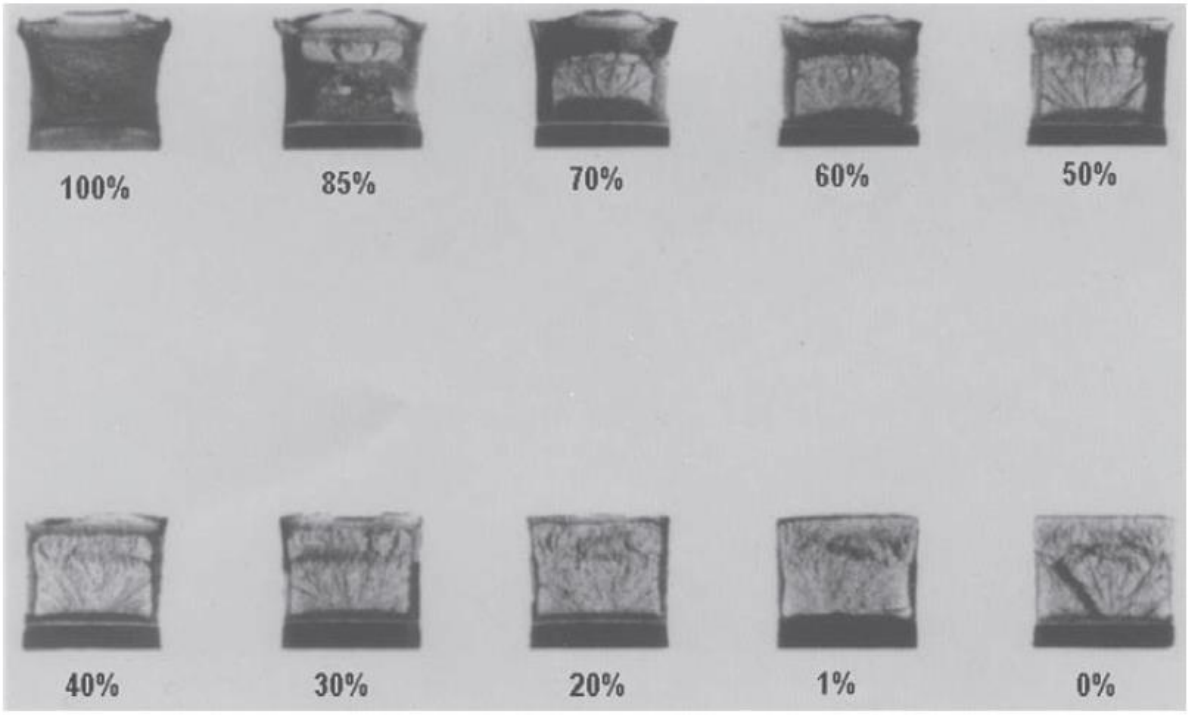
NOTE 1 Measure average dimensions *A* and *B* to the nearest 0,5 mm.

NOTE 2 Determine the per cent shear fracture using Table 3

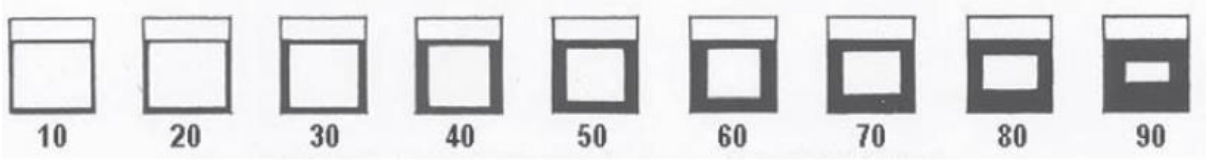
Figure 57 - Determination of per cent shear fracture.

B [mm]	A [mm] 1,0	1,5	2,0	2,5	3,0	3,5	4,0	4,5	5,0	5,5	6,0	6,5	7,0	7,5	8,0	8,5	9,0	9,5	10
	Percent shear																		
1,0	99	98	98	97	96	96	95	94	94	93	92	92	91	91	90	89	89	88	88
1,5	98	97	96	95	94	93	92	92	91	90	89	88	87	86	85	84	83	82	81
2,0	98	96	95	94	92	91	90	89	88	86	85	84	82	81	80	79	77	76	75
2,5	97	95	94	92	91	89	88	86	84	83	81	80	78	77	75	73	72	70	69
3,0	96	94	92	91	89	87	85	83	81	79	77	76	74	72	70	68	66	64	62
3,5	96	93	91	89	87	85	82	80	78	76	74	72	69	67	65	63	61	58	56
4,0	95	92	90	88	85	82	80	77	75	72	70	67	65	62	60	57	55	52	50
4,5	94	92	89	86	83	80	77	75	72	69	66	63	61	58	55	52	49	46	44
5,0	94	91	88	85	81	78	75	72	69	66	62	59	56	53	50	47	44	41	37
5,5	93	90	86	83	79	76	72	69	66	62	59	55	52	48	45	42	38	35	31
6,0	92	89	85	81	77	74	70	66	62	59	55	51	47	44	40	36	33	29	25
6,5	92	88	84	80	76	72	67	63	59	55	51	47	43	39	35	31	27	23	19
7,0	91	87	82	78	74	69	65	61	56	52	47	43	39	34	30	26	21	17	12
7,5	91	86	81	77	72	67	62	58	53	48	44	39	34	30	25	20	16	11	6
8,0	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	0
100 % shear shall be reported when either A or B is zero																			

Table 13 - Per cent shear for measurements in millimetres.



a) Fracture appearance charts and per cent shear fracture comparator



b) Guide for estimating fracture appearance

Figure 58 - Fracture appearance.

2.4.7. Test report

List of mandatory information to be contained in the test report:

A. reference to the standard test method (ISO 148-1);
B. identification of the test piece (e.g. type of steel and cast number);
C. size of the test piece, if other than the standard test piece;
D. temperature of the test or the conditioning temperature of the test specimens;
E. absorbed energy, KV_2, KV_8, KU_2, or KU_8, as appropriate;
F. 0 whether the specimen, or the majority of specimens in a group of specimens were broken (not required for material acceptance tests);
G. any abnormalities that could have affected the test.

Optional information:

A. test piece orientation (see ISO 3785)
B. initial potential energy of the testing machine, in joules;
C. lateral expansion
D. shear fracture appearance;
E. absorbed energy/temperature curve (see examples);
F. lateral expansion/temperature curve;
G. shear fracture appearance/temperature curve;
H. transition temperature and the criteria used for its (their) determination;
I. number of test pieces which were not completely broken in the test;
J. date (month and year) of the most recent full direct and indirect verifications;
K. measurement uncertainty of the absorbed energy (see chapter about uncertainty)

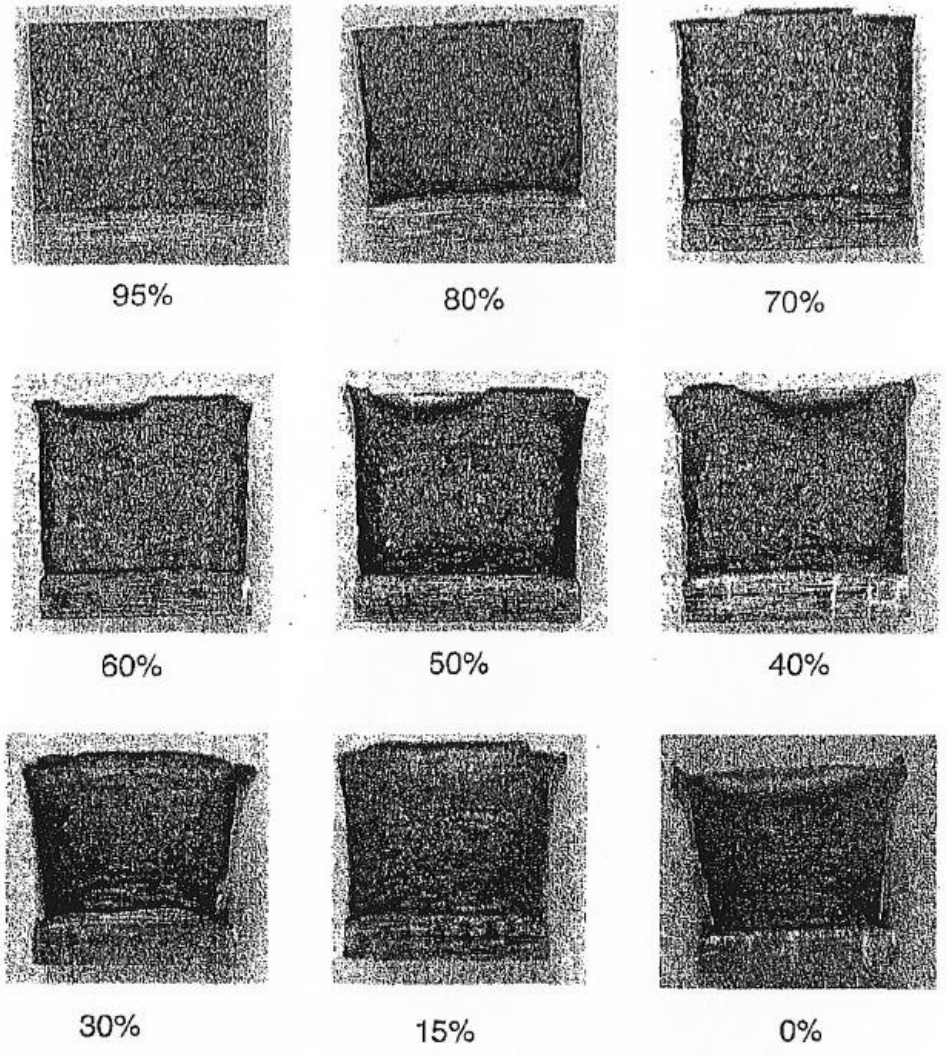


Figure 59 - Fracture appearance; percent of crystalline (brittle area; image taken from SEP 1670).

2.4.8. Example 1

The absorbed energy/temperature curve (KV/T curve) shows the energy absorbed as a function of the test temperature for a given type of test piece see Figure 60. In general, the curve is obtained by drawing a fitted curve through the individual values. The shape of the curve and the scatter of the test values are dependent on the material, the specimen shape and the impact velocity. In the case of a curve with a ductile-to-brittle transition zone, a distinction is made between the upper-shelf zone, transition zone and the lower-shelf zone.

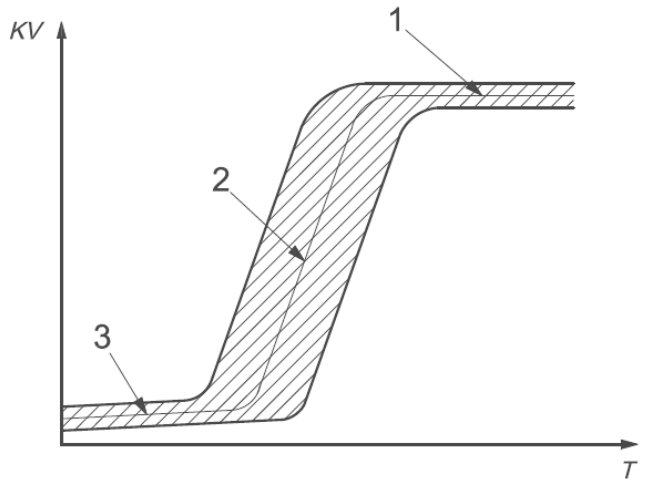
The transition temperature, Tt, characterizes the position of the steep rise in the absorbed energy/temperature curve. Since the steep rise usually extends over a fairly wide temperature range, there can be no generally applicable definition of the transition temperature. The following criteria have, among others, been found useful for determining the transition temperature:

The transition temperature, T_t, is the temperature at which

A. a particular value of absorbed energy is reached, e.g. KV_8 = 27 J,
B. a particular percentage of the absorbed energy of the upper-shelf value is reached, e.g. 50 %,
C. a particular portion of shear fracture occurs, e.g. 50 %, and
D. a particular amount of lateral expansion is reached, e.g. 0,9 mm.

The choice of the method used to define transition temperature should be specified in the product standard or specification, or by agreement.

The standard SEP 1670 could take as an example to perform a fit of the experimental data points and to select the proper testing temperature to obtain a transition curve. Such standard considers the crystalline % (brittle area in percentage) to determine the FATT50 (fracture appearance transition temperature at 50% of crystalline) or other FATT on the transition curve (see Figure 61); SEP 1670 also provide a testing plan with the number of samples to be tested at each temperature (see Figure 62).



Key

T temperature
KV absorbed energy

1 upper-shelf zone
2 transition zone
3 lower-shelf zone

Figure 60 - Absorbed energy/temperature curve shown schematically.

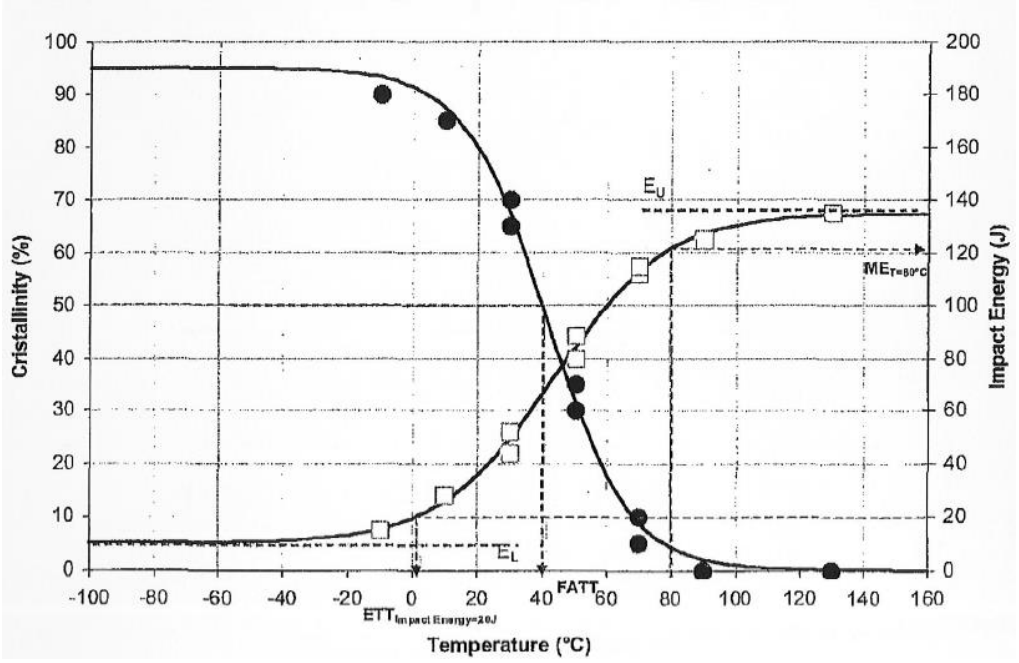


Figure 61 - Graph showing the principle for determining the characteristic values from the compensation curves (brittle fracture fraction and notch-impact energy as a function of the temperature); note EU is the upper shelf absorbed energy, E_L is the lower shelf absorbed energy and $ME_{T=80°C}$. is the impact energy at 80°C, $ETT_{Impact\ Energy=20J}$ is the temperature at 20 J of absorbed energy and FATT is the temperature at 50% of Crystallinity.

Temperature in °C	Number of samples
T_{start}	1
T_{start} – 20 °C	2
T_{start} – 40 °C	1
T_{start} – 60 °C	1
T_{start} + 20 °C	2
T_{start} + 40 °C	1
T_{start} + 80 °C	1
T freely selectable	1

Figure 62 - SEP 1670 also provide a testing plan with the number of samples to be tested at each temperature.

2.4.9. Example 2

Test specimen taken from a butt weld with an examination length of 40 mm and examination thickness of 10 mm.

Without any requirement about notching and test method:

- Basic denomination: BW / (L_f a_f)
- For this example: BW / [40 · 10)

With additional requirement (square face notching and test method):

- Comprehensive denomination: BW / (L_f a_f)/ S_r (See Figure 55)
- For this example: BW / [40 · 10) / S_r (See Figure 55)

2.5. Fracture Tests of Welded Joints

2.5.1. Foreword

The Fracture Test is a simple method to investigate the quality of a joint fabricated through a fusion welding process. Differently from a tensile test, neither maximum load for the rupture nor the displacement are recorded during the test; the lone scope of the test is to rupture the weld to reveal and examine the flaws or the welding imperfections present into the joint.

The purpose of such method is to provide a parallel control to the volumetric non-destructive teste (e.g. radiographic test and ultrasonic test) where they can be difficult to apply or when a further examination is required to determine the quality of a weld. Therefore, together with the execution of the fracture test, a visual examination (according to ISO 17637) is performed and the quantification of the imperfections is conducted by applying the standards ISO 5817 and ISO 10042 and the quality level of the joint is determined. After that, the obtained quality level is compared with the requirements to verify the compliance of the result.

In this chapter the normative references to perform the fracture test are cited and the test method of ISO 9017 (fracture test) is reported and described.

2.5.2. References

- ISO 9017 Destructive tests on welds in metallic materials - Fracture test
- ISO 5817 Welding - Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding
- excluded) - Quality levels for imperfections
- ISO 10042 Welding - Arc-welded joints in aluminium and its alloys - Quality levels for imperfections
- ISO 17637 Non-destructive testing of welds - Visual testing of fusion-welded joints

2.5.3. Introduction

The scope of the fracture test is to examine the fracture surface of a welded joint (fusion welded joint) to identify and quantify the imperfections according to the standards ISO 17637 (visual examination) and ISO 5817 or ISO 10042 (quality levels for imperfections on fusion-welded joints in steel, nickel, titanium and their alloy or for aluminium and its alloys respectively). Therefore, the joint has to be

always ruptured in two parts to reveal the fracture surfaces to be examined. A fracture test where no fracture is obtained is not valid.

The test method described in ISO 9017 specifies the sizes of test specimen and the procedures for carrying out fracture tests in order to obtain information about types, sizes and distribution of internal imperfections such as porosities, cracks, lack of fusion, lack of penetration and solid inclusions on the fracture surface. The test described in ISO 9017 is applicable to metallic materials in all forms of product with joints made by any fusion welding process with a thickness greater or equal to 2 mm.

The method suggests different techniques to fracture the joint through the weld metal in order to examine the fracture surface. The test (fracture of the joint) shall be carried out at room temperature (23 ± 5°C); moreover, the use of notches is recommended to better fracture the specimens. Furthermore, notch dimensions and temperature can be varied to induce the fracture. Basically, in order to better induce the fracture, the testing temperature can be reduced (e.g. for ductile materials) and the size of the notched can be increased.

Finally, the fracture can be induced by bending or tension, static or dynamic loading.

In the following table, the list of terms adopted in ISO 9017 are reported together with their descriptions and definitions (see Table 14).

Term	Definition	Description
-	Test piece	Sample to be examined where the specimens are taken (see Figures 63 to 66)
-	Test specimen	Portion of the test piece taken to perform the fracture test (see Figures 68 to 70)
L_f	Examination length	Length of the test specimen measured along the weld axis between any side notches (measured in [mm])
ΣL_f	Total examination length	Sum of the lengths of all the test specimens comprising the test piece, measured along the weld axis, of the fracture faces between the side notches of the test specimens (measured in [mm])
a_f	Examination thickness	thickness of the fracture area for each test specimen (measured in [mm])
A_f	Examination area	product of the examination length and the examination thickness for each test specimen (measured in [mm^2])
ΣA_f	Total examination area	sum of all examination areas (measured in [mm^2])
W	Original width	Original width of the test specimen (see Figure 68)

X	Total length	Total length of the weld in the test piece
t, t_1, t_2	-	Thickness of test piece (measured in [mm]), see Figure 69 and 70
l_1, l_2	-	Length of test piece (measured in [mm])
D	-	Outside diameter of tube (measured in [mm])
FW	Fillet weld	Weld performed at the corner between two plates or one plates and a pipe (e.g. one perpendicular to the other); see Figures 65 and 66.
BW	Butt weld	Weld performed between two plates of two pipes to extend them along their longitudinal axis (e.g. pipes) or along their width (e.g. plates); see Figures 63 and 64.
S	Side notch	Notch on the side (or sides) of the weld
F	Face notch	Longitudinal notch on the face of the weld
R	Root notch	Longitudinal notch on the root of the weld
q	Square notch	See Figure 67
r	Round notch	See Figure 67
s	Sharp notch	See Figure 67
S_q	Side notch	Square (q) Side notch (S)
S_r	Side notch	Round (r) Side notch (S)
S_s	Side notch	Sharp (s) Side notch (S)
F_q	Face notch	Square (q) Face notch (F)
F_r	Face notch	Round (r) Face notch (F)
F_s	Face notch	Sharp (s) Face notch (F)
R_q	Root notch	Square (q) Root notch (R)
R_r	Root notch	Round (r) Root notch (R)
R_s	Root notch	Sharp (s) Root notch (R)

Table 14 - List of terms and definitions taken from ISO 9017.

2.5.4. Test specimens

The dimensions of the test specimens are defined in the figures reported from Figure 63 to Figure 66; the test piece shall provide sufficient test specimens for the required ΣL_f and ΣA_f. The values of L_f and A_f and the number of test specimens shall be specified by the application standard or by agreement between the contracting parties. Welded joints in plates shall be cut transversely to the welded joint in test specimens of approximately equal weld length. The weld axis shall remain in the middle of the test specimen for butt welds.

For welded joints in pipe, the test piece shall provide at least two test specimens. When carrying out bend tests, equal numbers of specimens shall be tested with the root in tension and the face in tension. If the pipe diameter is too small for removing the required number of test specimens, additional test pieces shall be welded.

Each test piece shall be marked to identify its exact location in the manufactured product or in the joints from which it has been removed. When removed from the test piece, each test specimen shall be marked.

The extraction method shall be choice to avoid the introduction of detrimental thermal or mechanical effects. As a general rule, a portion 25 mm from both ends of the test welds shall be discarded, unless information about the ends of the welds is required [e.g. start/stop imperfections]. Depending on the materials of the joint a proper cutting method shall be selected according to following considerations:

- The steels test specimens shall be cut by thermal cutting or by mechanical means;
- other metallic materials shall only be cut mechanically.

Fracture of welds in plates or pipes may be assisted by one or more of the following:

- removing the weld reinforcement
- notching both edges of the weld (side notching);
- notching into the reinforcement (longitudinal notching).

Depending on the ductility of the weld metal, square, round or sharp notches may be used, (see Figures from 67 to 70]. For materials of high ductility (e.g. aluminium and copper, sharp notches can be recommended).

The depth of the notches shall be sufficient to induce fracture in the weld. The notch depth should be such that:

- side notch: $L_f \geq 70\%$ W or $\Sigma L_f \geq 60\%$ X
- longitudinal notch: $a_f \geq 80$ % t or t_1 or t_2

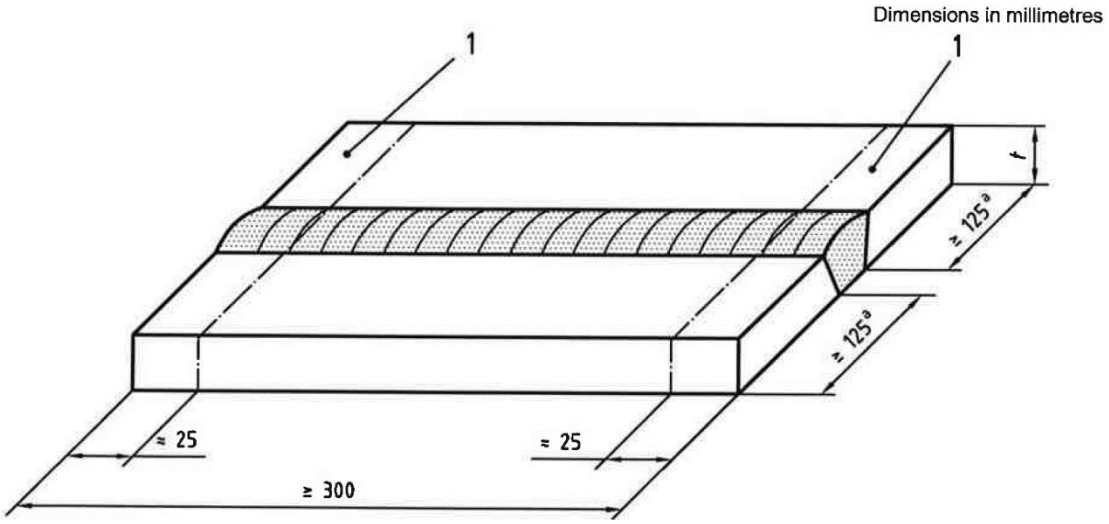


Figure 63 - Test piece for butt welds in plate; Note: 1 = discard; a ≥ 150 mm for materials of high thermal conductivity (e.g. aluminium and copper).

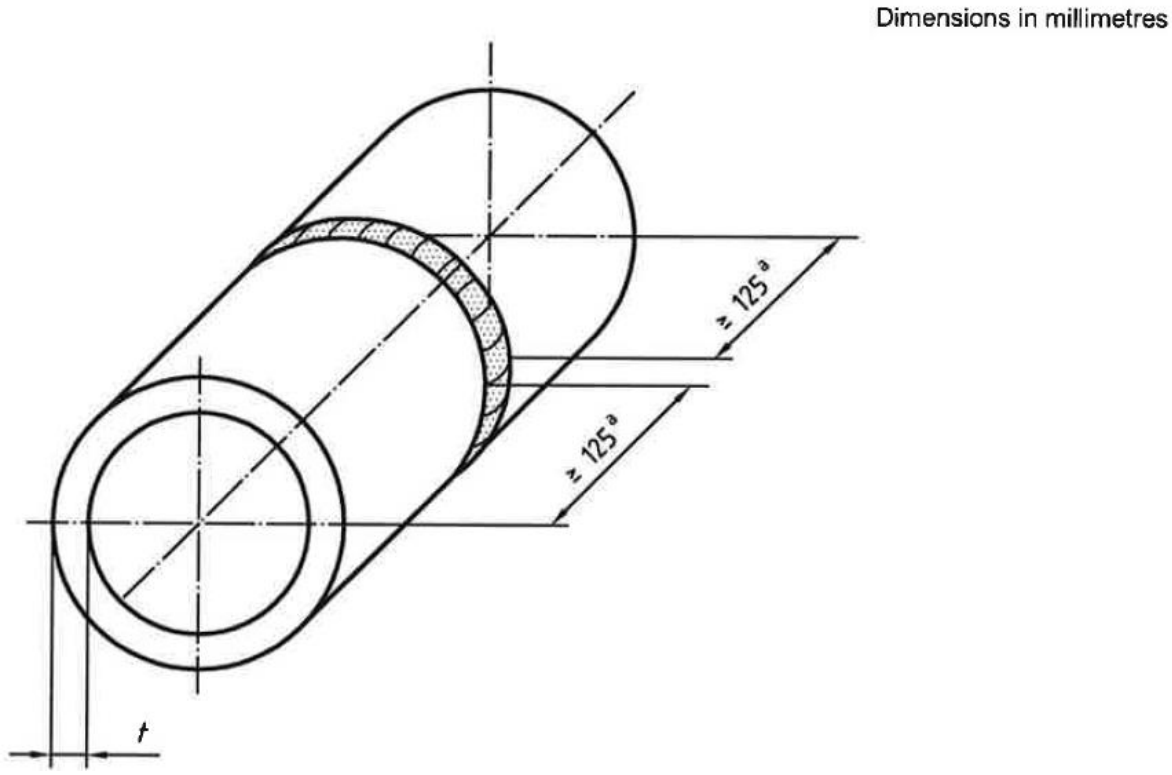


Figure 64 - Test piece for butt welds in pipe; Note: a ≥ 150 mm for materials of high thermal conductivity (e.g. aluminium and copper).

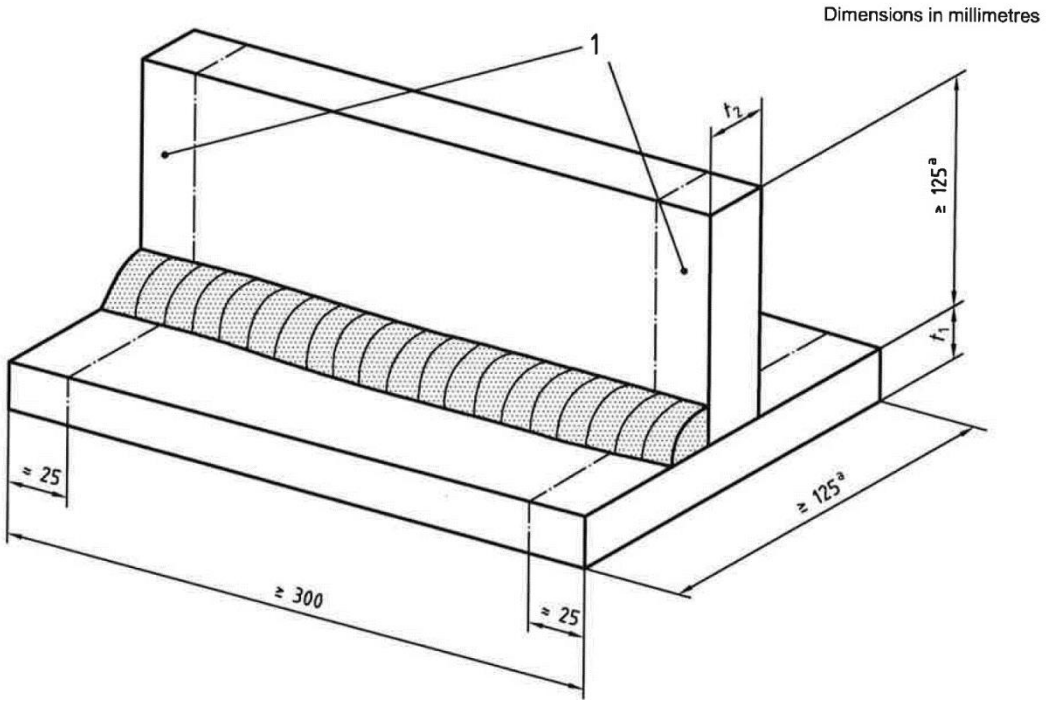
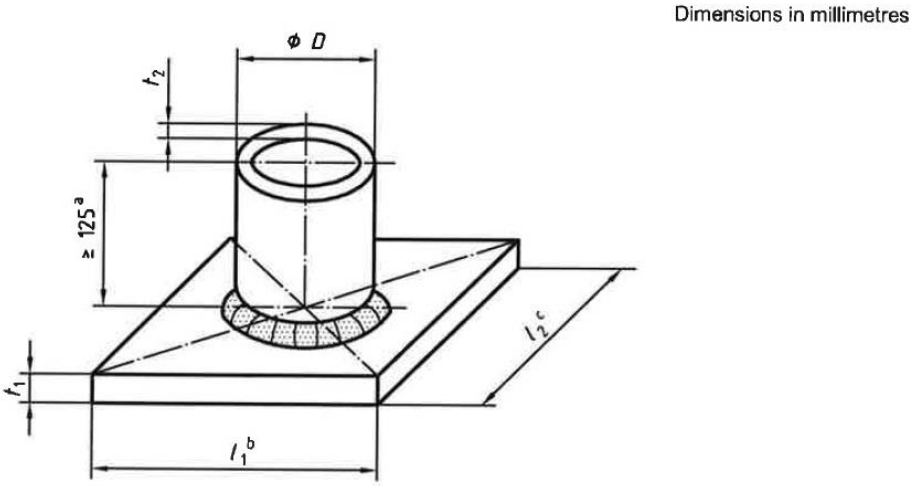


Figure 65 - Test piece for fillet welds on plate; Note: a ≥ 150 mm for materials of high thermal conductivity (e.g. aluminium and copper).



a ⩾ 150 mm for materials of high thermal conductivity (e.g. aluminium and copper)

b $l_1 \approx l_2$; $l_1 \geqslant (D + 100)$

c $l_2 \geqslant (D + 100)$

Figure 66 - Test piece for fillet welds on pipe.

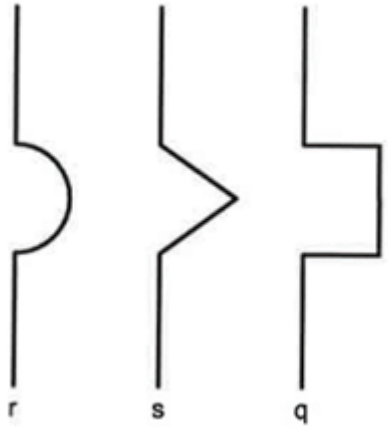


Figure 67 - Notch profiles (r = round; s = sharp; q = root).

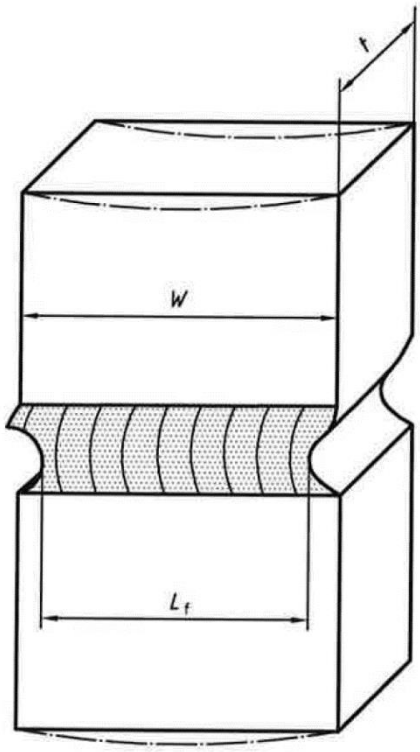


Figure 68 - Side notches (note full lines are for plates while dotted/dashed lines are for pipes).

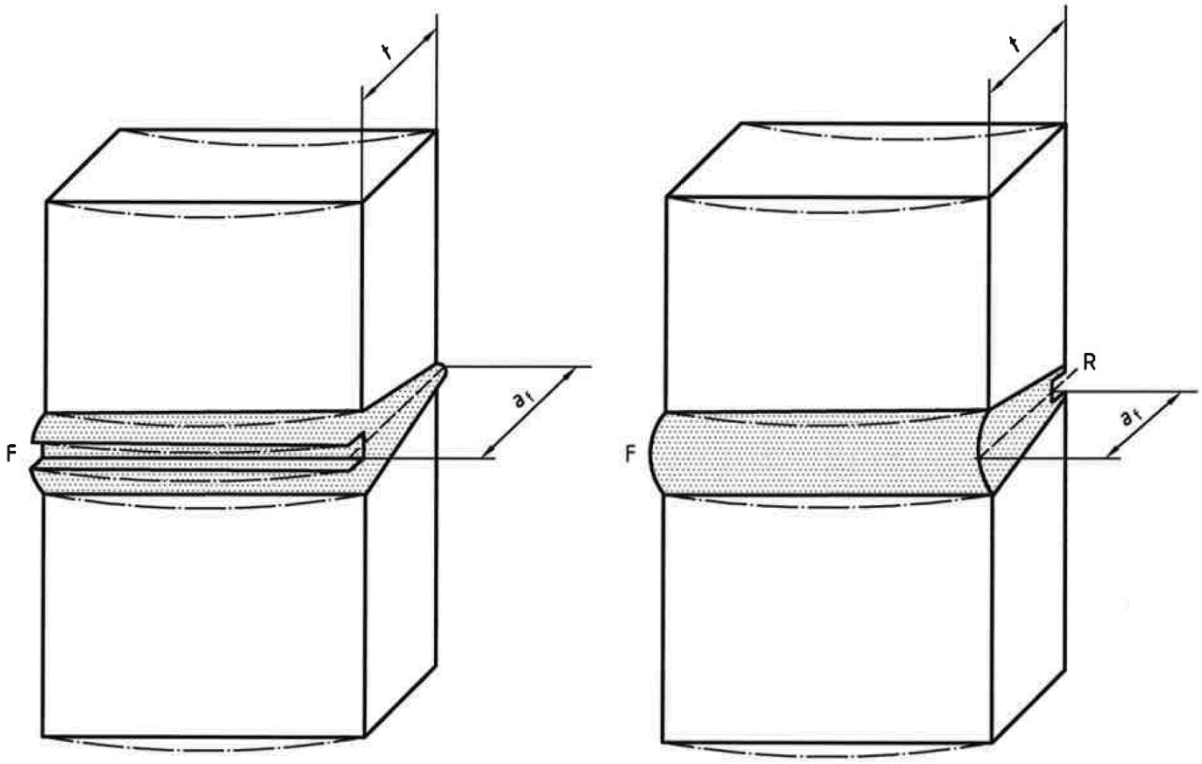


Figure 69 - Longitudinal notches in butt welds, on the left: Face notches; on the right: Root notches (note full lines are for plates while dotted/dashed lines are for pipes).

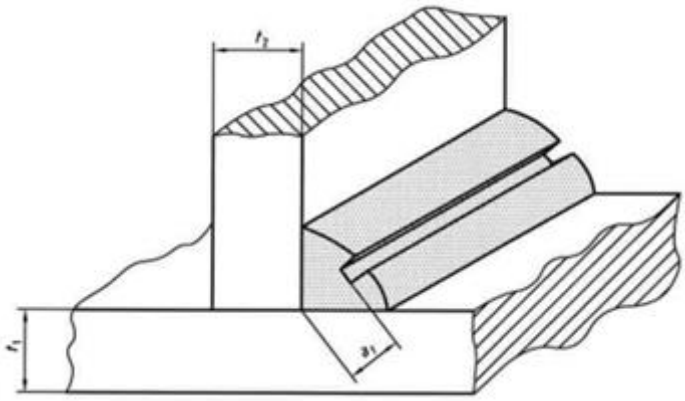


Figure 70 - Longitudinal notches in fillet welds.

2.5.5. Test procedure

Fracture tests may be carried out by:

- dynamic strokes (e.g. with a hammer); see Figures 71 a) to c) for BW and Figure 72 a) for FW

- applying a load by pressing in a vice, bending machine or workshop press; see Figures 71 d) to f) for BW and Figures 72 c) and c) for FW
- applying a load by tension (e.g. with a tensile test machine), see Figure 71 g)

For ductile materials, it can be useful to have a minimum distance (b_{min}) between the notch and the jaws of the clamps of device see Figure 71 c). Furthermore, for ductile weld metals such as austenitic steels, aluminium, copper nickel and their alloys, it can be necessary to restrict the thickness of the test specimen and the throat thickness, increase the width of the notch, decrease the radius of the notch and increase the severity (stroke loading, hammer loading) of the test, if fracture is required in the weld metal. For ductile weld metals such as ferritic steel, it can be necessary to cool the test specimen.

Thicker materials may be fractured by hammer strokes. When a bending machine is used, the diameter of the former shall be chosen in such a way that the fracture occurs without the need for alternate bending. Bending may be carried out either with the weld perpendicular or transverse to the direction of the applied force according to Figures 71 c) to f). The lowest limit for the test for aluminum is approximately 8 mm of thickness.

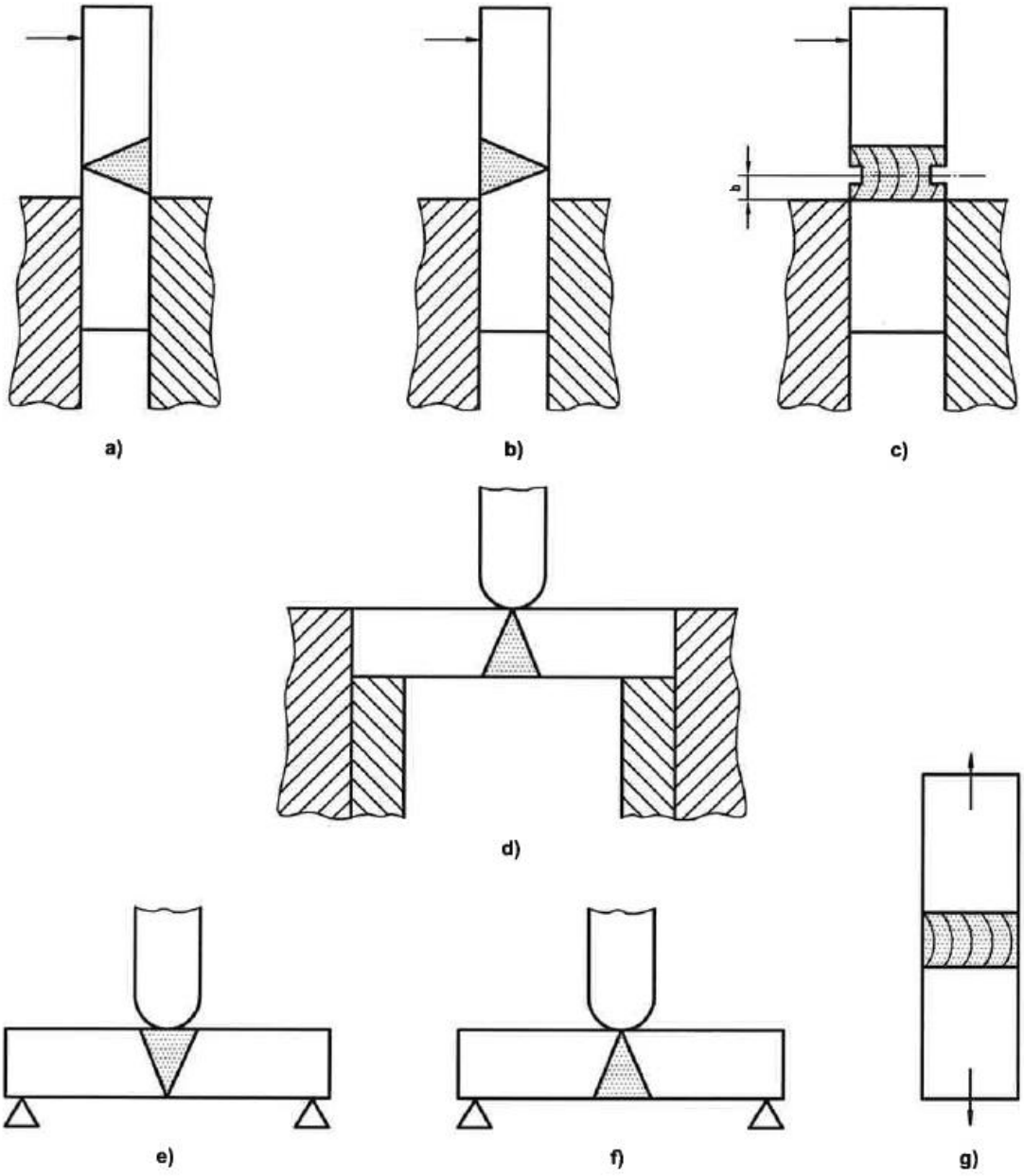


Figure 71 - Examples of test methods on BW (Notches according to Figures 47 to 49).

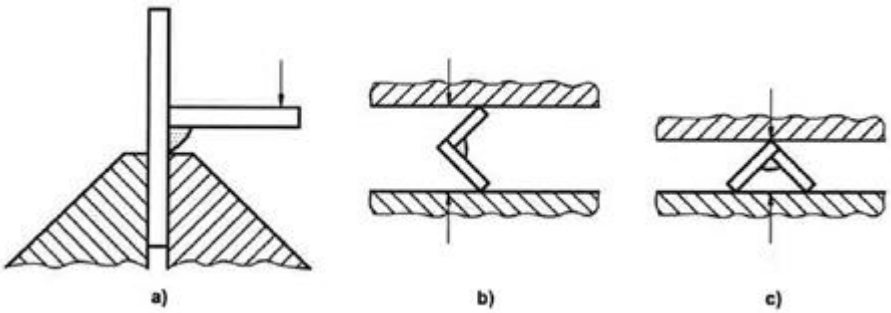


Figure 72 - Examples of test methods on FW (Notches according to Figures 47 and 50).

2.5.6. Test result

After the rupture of the specimen, the fracture surface shall be examined visually in accordance with ISO 17637. For clear detection and identification of imperfections a low magnifying glass (e.g. up to five times of magnification) may be used.

A full description of the appearance of the fracture surface and the type and location of any imperfection present shall be reported. It shall be stated that the quality has been evaluated in accordance with ISO 5817 or ISO 10042. The quality level is specified by the application standard or by agreement between the contracting parties.

The test report shall contain the following information:

- a reference to the applied standard test method (ISO 9017);
- the identification of the test specimen;
- the specimen denomination in accordance with Table 14;
- records of types, locations and sizes of all unacceptable imperfections in accordance with the relevant quality level.

2.5.7. Example 1

Test specimen taken from a fillet weld with an examination length of 40 mm and examination thickness of 10 mm.

Without any requirement about notching and test method:

- Basic denomination: FW / (L_f a_f)
- For this example: FW / [40 · 10)

With additional requirement (square face notching and test method):

- Comprehensive denomination: FW / (L_f a_f)/ F_q (See Figure 70)
- For this example: FW / [40 · 10) / F_q (See Figure 70)

2.5.8. Example 2

Test specimen taken from a butt weld with an examination length of 40 mm and examination thickness of 10 mm.

Without any requirement about notching and test method:

- Basic denomination: BW / (L_f a_f)
- For this example: BW / [40 · 10)

With additional requirement (square face notching and test method):

- Comprehensive denomination: BW / (L_f a_f)/ S_r (See Figure 68)
- For this example: BW / [40 · 10) / S_r (See Figure 68)

2.5.9. Example 3

An example of a typical test report, see Figure 73.

Example of a test report

No. .....

According to pWPS .....

According to test result "fracture test"

test result "....."

Manufacturer: .....

Purpose of the examination: .....

Form of product: .....

Parent metal: .....

Consumable: .....

Denomination of test piece: .....

Table A.1 — Fracture test in accordance with ISO 9017

Test specimen	Denomination	Results	
		Type and size of imperfections	Quality level

Examiner or examining body: Certified by:

....

(name, date and signature) (name, date and signature)

Figure 73 - Example of a test report according to ISO 9017.

2.5.10. Example 4

An example of the fracture surfaces of four BW specimens with round side notches (S_r) and with notched reinforcement (round face notch, F_r) after fracture, see Figure 74.

The specimens on the left shows a ductile morphology of the fracture surface with no relevant flaws and no imperfections (acceptable surface), the specimens on the right (note two halves of different specimens are reported) revealed some porosities and other imperfections (highlighted by a white dashed rectangle) on the fracture surfaces (see Figure 74).

Furthermore, on the same figure, the examination length (L_f) and the examination thickness ($_{af}$) are reported together with the original thickness ($_t$) and the original width of the specimen (*W*).

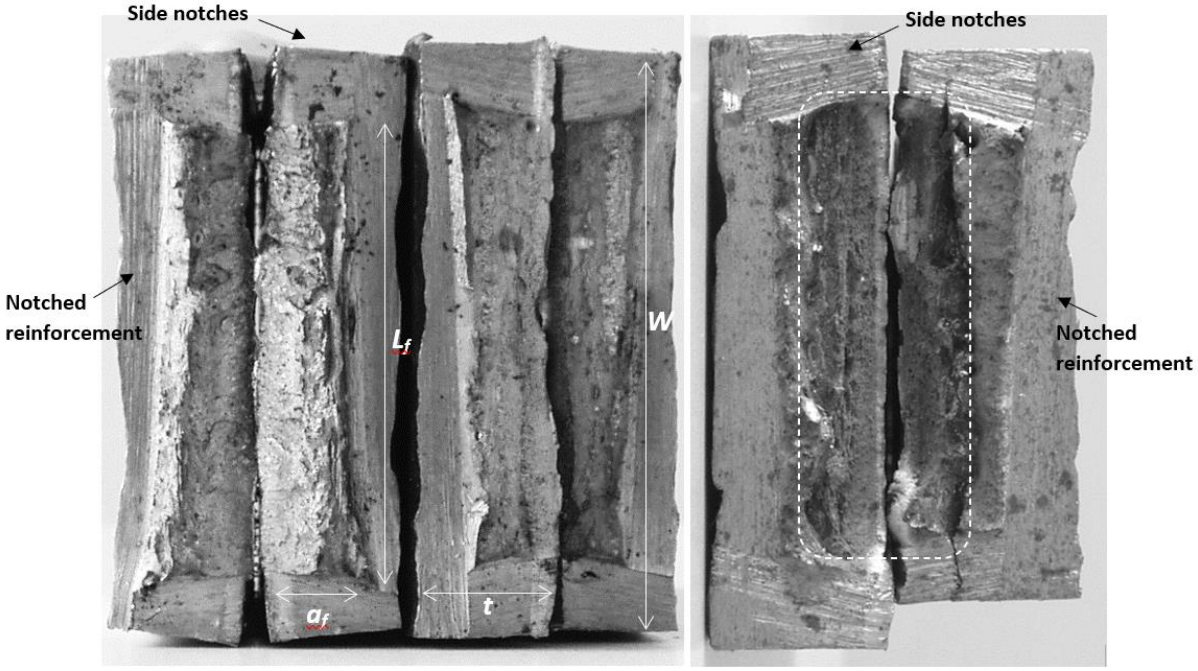


Figure 74 - Fracture surfaces of BW specimens with Sr and notched reinforcement (Fr).

2.6. Hardness Tests of Welded Joints

2.6.1. Definition of hardness

Hardness is the property of a material that enables it to resist plastic deformation, usually by indentation. It is determined by measuring the permanent depth of the indentation. Given a fixed load and a specific indenter, the smaller the indentation is, the harder the material is. However, hardness may also be assessed by the resistance to scratching or cutting by another material.

Hardness is not an intrinsic material property dictated by precise definitions in terms of fundamental units of mass, length and time. A hardness property value is the result of a defined measurement procedure.

$$HV = \frac{2F \sin\frac{136^o}{2}}{d^2}$$

$$HV = 1.854 \cdot \frac{F}{d^2}$$

Where *F* is the applied load (measured in kilograms-force), *d* = Arithmetic mean of the two diagonals, *d1* and *d2* in mm and d^2 is the area of the indentation (measured in square millimetres).

When the average diagonal of the indentation has been determined the Vickers hardness may be calculated from the formula, but we can also hardness use conversion tables.

Vickers hardness, HV, is designated as shown in the following example.

2.6.2. Method for hardness testing

Typically, three types of testing methods are used to measure hardness of metals, i.e., Brinell hardness test, Rockwell hardness test, and Vickers hardness test. They distinguish from each other by the use of different indenters. A 10 mm diameter hardened steel or carbide ball usually is used as an indenter in the Brinell hardness test, a diamond or steel cone in the Rockwell hardness test, and a pyramidal shaped diamond indenter in the Vickers hardness test.

The hardness value is dependent on the defined measurement procedure. And it cannot be defined in terms of fundamental units of mass, length and time. The most used method being the Vickers hardness test.

2.6.3. Vickers hardness test

Vickers hardness test is the standard method for measuring the hardness of metals, particularly those with extremely hard surfaces. The indenter used is a square-based pyramid whose opposite sides meet at the apex at an angle of 136º (Figure 75a). The diamond is pressed into the surface of the material at a load. After a dwelt time (10 to 15 seconds), the load is removed.

And that, the two diagonals of the indentation left in the surface of the material after removal of the load (Fig.75b) are measured under a calibrated microscope due to the small size of the indent (generally between 0,020 mm and 1,400 mm) and heir average calculated.

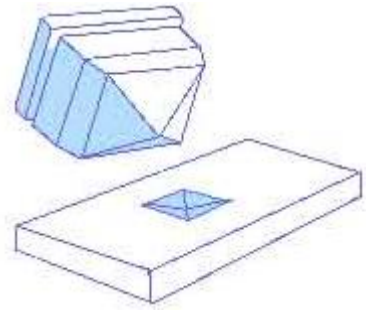


Figure 75a - Vickers hardness test

(http://www.hardnesstesters.com/hardness-method-2.htm).

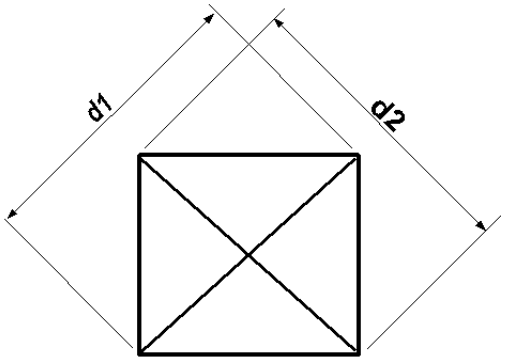


Figure 75b - the residual indent on the surface.

The Vickers number (HV) is calculated by the following formula:

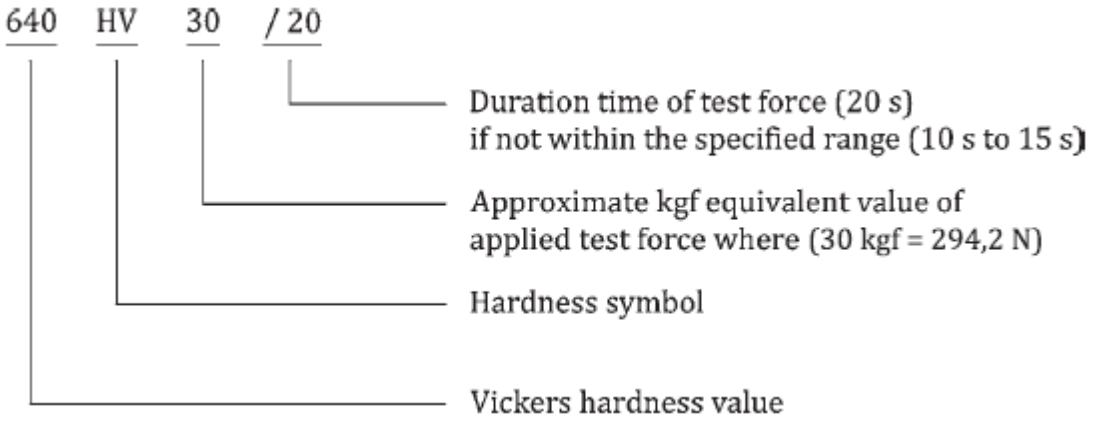
$$HV = \frac{2F \sin\frac{136^o}{2}}{d^2}$$

$$HV = 1.854 \cdot \frac{F}{d^2}$$

Where *F* is the applied load (measured in kilograms-force), *d* = Arithmetic mean of the two diagonals, *d1* and *d2* in mm and d^2 is the area of the indentation (measured in square millimetres).

When the average diagonal of the indentation has been determined the Vickers hardness may be calculated from the formula, but we can also hardness use conversion tables.

Vickers hardness, HV, is designated as shown in the following example.



Other different loading settings (1, 2, 5, 10, 30, 50 and 100 kgf) give practically identical hardness numbers on homogenous material, which is much easier than in the arbitrary changing of scale, as with the other hardness testing methods. The advantages of the Vickers hardness test are that

extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments.

The resolution required of the diagonal measuring system depends on the size of the smallest indentation to be measured and shall be in accordance with Table 15. In determining the resolution of the measuring system, the resolution of the microscope optics, the digital resolution of the measuring scale and the step-size of any stage movement, where applicable, should be taken into account.

Diagonal length, *d* mm	**Resolution of the measuring system**
0,020 ≤ *d* < 0,080	0,000 4 mm
0,080 ≤ *d* ≤ 1,400	0,5 % of *d*

Table 15 - Resolution of the measuring system.

Hardness conversion between different methods and scales cannot be made mathematically exact for a wide range of materials. Different loads, different shape of indenters, homogeneity of specimen, cold working properties and elastic properties all complicate the problem. All tables and charts should be considered as giving approximate equivalents, particularly when converting to a method or scale which is not physically possible for the particular test material and thus cannot be verified. An example would be converting the HV 10 value on a thin coating to the HRC equivalent.

Links to the Hardness Conversion Tables and Charts are below:

Hardness Conversion Table

Hardness Conversion Chart

Chart of Brinell, Vickers and Ultimate Tensile Strength Equivalents (1)

Hardness Conversion Chart related to Rockwell C Hardness Scales (hard materials)

Estimated Hardness Equivalent Chart related to Rockwell C and Vickers (hard materials)

HV, MPa and GPa Conversion Calculator

Before a Vickers hardness testing the machine shall be verified, the machine shall be checked to ensure that it is properly set up in accordance with the manufacturer's instructions.

Especially, it should be checked that:

a) the plunger holding the indenter is capable of sliding in its guide without any friction or excessive side play;
b) the indenter-holder is firmly mounted in the plunger;
c) the test force can be applied and removed without shock, vibration or overshoot and in such a manner that the readings are not influenced;

d) the diagonal measuring system:
   1) if integral with the machine, the change from removing the test force to measuring mode does not influence the readings;
   2) the illumination device of the measuring microscope produces uniform lighting of the whole observed field with enough contrast between the indentation and the surrounding surface to determine the boundary clearly;
   3) the centre of the indentation is in the centre of the field of view, if necessary.

Direct verification of a Vickers hardness test machine involves:

a) calibration of the test force;
b) verification of the indenter;
c) calibration and verification of the diagonal measuring system;
d) verification of the testing cycle.

Direct verification should be carried out at a temperature of (23 ± 5) °C. If the verification is made outside this temperature range, this shall be stated in the verification report.

The instruments used for verification and calibration shall be traceable to national standards.

Each test force used within the working range of the testing machine shall be measured. Whenever the indenter position affects the applied force, this shall be done at not less than three positions of the plunger uniformly spaced throughout its range of movement during testing. For testing machines whose test force is shown not to be influenced by the position of the plunger, e.g. closed-loop controlled loading system, the test force can be calibrated in one position.

Three readings shall be taken for each test force, *F*, at each position of the plunger. Immediately before each reading is taken, the indenter shall be moved in the same direction as during testing.

The testing machine shall be verified by testing reference blocks that have been calibrated in accordance with ISO 6507-3. The blocks shall have been calibrated using the same test forces that the machine will use for future testing. When verifying more than one test force, at least two reference blocks shall be selected from the hardness ranges specified below for each test force that the machine will be verified. The set of blocks needed for verifying the machine for all the test forces shall be chosen so that at least one reference block from each hardness range is used for the verifications. When verifying testing machines using only one test force, three reference blocks shall be used, one from each of the three hardness ranges specified below.

The hardness ranges should be chosen, when possible, to replicate the hardness levels most commonly tested when using the specific test forces.

— <250 HV

— 400 HV to 600 HV

— >700 HV

On each reference block, five indentations shall be made and measured. The test shall be carried out in accordance with ISO 6507-1. Only the calibrated surfaces of the test blocks are to be used for testing.

Direct verifications shall be performed according to the schedule given in Table 16. It is recommended that direct verifications be performed every 12 months.

Indirect verification shall be performed at least once every 12 months and after a direct verification has been performed.

Requirements of verification	Force	Diagonal measuring system	Test cycle	Indentera
Before setting to work first time	x	x	x	x
After dismantling and reassembling, if force, diagonal measuring system or test cycle are affected.	x	x	x	
Failure of indirect verification[b]	x	x	x	
Indirect verification > 13 months ago	x	x	x	
In addition, it is recommended that the indenter be directly verified after 2 years of use. Direct verification of these parameters may be carried out sequentially (until the machine passes indirect verification) and is not required if it can be demonstrated, for example, by tests with a reference indenter, that the indenter was the cause of the failure.				

Table 16 - Direct verifications of hardness testing machines.

Measurement uncertainty analysis is a useful tool to help determine sources of error and to understand differences between measured values. This annex gives guidance on uncertainty estimation but the values derived are for information only, unless specifically instructed otherwise by the customer. The criteria specified in this document for the performance of the testing machine have been developed and refined over a significant period of time.

When determining a specific tolerance that the machine needs to meet, the uncertainty associated with the use of measuring equipment and/or reference standards has been incorporated within this tolerance and it would therefore be inappropriate to make any further allowance for this uncertainty by, for example, reducing the tolerance by the measurement uncertainty.

This applies to all measurements made when performing a direct or indirect verification of the machine. In each case, it is simply the measured value resulting from the use of the specified measuring equipment and/or reference standards that is used to assess whether or not the machine complies with this document. However, there may be special circumstances where reducing the tolerance by the measurement uncertainty is appropriate.

2.6.4. References (last edition)

- ISO 6507-1: Metallic materials – Vickers hardness test – Part 1: Test method
- ISO 6507-2: Metallic materials – Vickers hardness test – Part 2: Verification and calibration of testing machines
- ISO 6507-3: Metallic materials – Vickers hardness test – Part 3: Calibration of reference blocks
- ISO 6507-4: Metallic materials – Vickers hardness test – Part 4: Tables of hardness values
- ISO 4516: Metallic and other inorganic coatings — Vickers and Knoop microhardness tests

- EN ISO 14271: Resistance welding - Vickers hardness testing (low-force and microhardness) of resistance spot, projection, and seam welds
- ISO 22826: Destructive tests on welds in metallic materials — Hardness testing of narrow joints welded by laser and electron beam (Vickers and Knoop hardness tests)
- EN ISO 4498: Sintered metal materials, excluding hardmetals - Determination of apparent hardness and microhardness
- ISO 18265: Metallic materials – Conversion of Hardness Values
- EN ISO 14577-1: Metallic materials - Instrumented indentation test for hardness and materials parameters - Part 1: Test method
- EN ISO 14577-2: Metallic materials - Instrumented indentation test for hardness and materials parameters - Part 2: Verification and calibration of testing machines
- EN ISO 15614-1: Specification and qualification of welding procedures for metallic materials. Welding procedure test. Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys

2.7. Exercises for the classroom

The following theoretical and practical exercises should be answered by the trainees after the theoretical training sessions of **CHAPTER 2**, to assess their progress on the acquired knowledge.

2.7.1. Tensile Tests of Metals at Room Temperature Exercises

2.7.1.1. Exercise 1

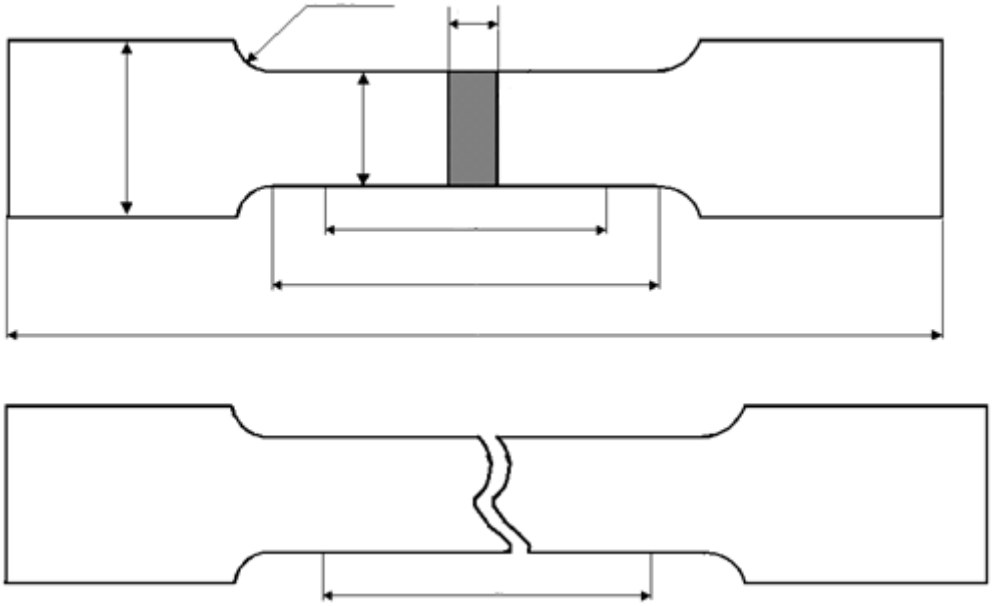
Answer the following questions to assess your understanding of the concepts. Provide brief and concise answers.

1. What is the purpose of tensile testing?
2. What are the key components of a typical tensile testing machine?
3. Explain the difference between engineering stress and true stress.
4. Define the terms elastic deformation, plastic deformation, and fracture in the context of tensile testing.
5. What is the yield strength of a material, and how is it determined?
6. How is ultimate tensile strength (UTS) different from yield strength?
7. Describe the concept of strain hardening (work hardening) and its effect on a material's tensile properties.
8. What is the significance of the elongation and reduction in area measurements in tensile testing?
9. How does temperature affect the mechanical properties of a material during tensile testing?

2.7.1.2. Exercise 2 | Demonstration

Please fill the missing symbols in the figure from list below and explain the meaning of symbols.

- a_0 –
- b_0 –
- b_1 -
- L_c –
- L_0 –
- L_t –
- L_u –
- R -



2.7.2. Tensile Tests of Welded Joints with Butt Welds, Cruciform Joints, Overlap Joints, and Joints with Fillet Welds Exercises

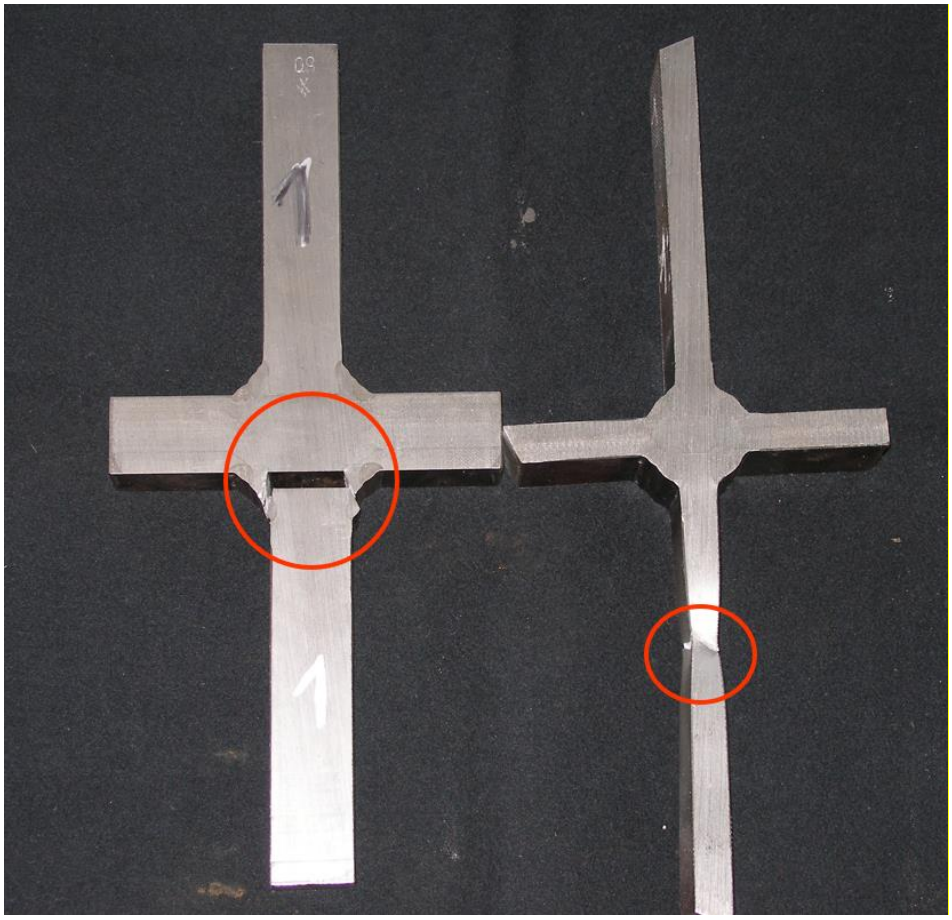
2.7.2.1. Exercise 1

Answer the following questions to assess your understanding of the concepts. Provide brief and concise answers.

1. Describe the requirements for selecting a test specimen from a welded joint, including its location and machining process.
2. Explain the dimensions and surface conditions that the test specimen should conform to.
3. Discuss the situations where multiple test specimens may be required to cover the full thickness of a joint and the related thickness considerations.
4. Explain the load application process and fracture criteria for the test specimen during tensile testing.
5. Describe the importance of examining the fractured surfaces of the test specimen and recording any imperfections that may have influenced the test results.
6. List the information that should be included in the test report.

2.7.2.2. Exercise 2 | Demonstration

Indicate which method of failure of the specimen in the cross joint tensile test is correct.



2.7.3. Bend Test of Metals and Welded Joints Exercises

2.7.3.1. Exercise 1

Define how you will act in the case of failure of the specimen during the bend test, chose one of the following options and explain your answer:

A. discard the specimen and ask for a new one to the workshop
B. call the customer to inform the welding coupon is not acceptable
C. measure the dept of the crack and calculate the effective section thus to obtain the real bending stress on the cracked specimens
D. after the measure of the flaw on the tension surface you detect its length is less than 3 mm, therefore you further bend the specimen to increase such length up to a value greater than 3 mm thus confirm the not acceptable result (failure of the specimen)
E. you measure just the angle at which the rupture of the specimen took place (in the case of the specimen was ruptures thus was not possible to continue the test)
F. you measure the elongation at which the rupture of the specimen took place (in the case of the specimen was ruptures thus was not possible to continue the test)

G. if you evaluate the specimen is failed you will put in the test report the maximum angle achieved by the specimen during the bend test and you will put in the notes the length of the detected rupture or flaw
H. if, during the bend test, you see the comparison of a flaw you immediately interrupt the test thus to measure the length of the flaw and to establish if it is acceptable or not
I. if, during the bend test, you see the comparison of a flaw you will continue the test until the end but a lower speed than the beginning
J. if, during the bend test, you see the comparison of a flaw you will continue the test until the end and then you will not perform the tests on the remaining specimens of the same sample because it is not necessary
K. if you see the comparison of a defect on the tension surface of the specimen during the test, you will immediately stop the test thus repeat it on the same specimen but bending it in the reverse way thus the on the opposite face where the flaw is compared is now the tension face

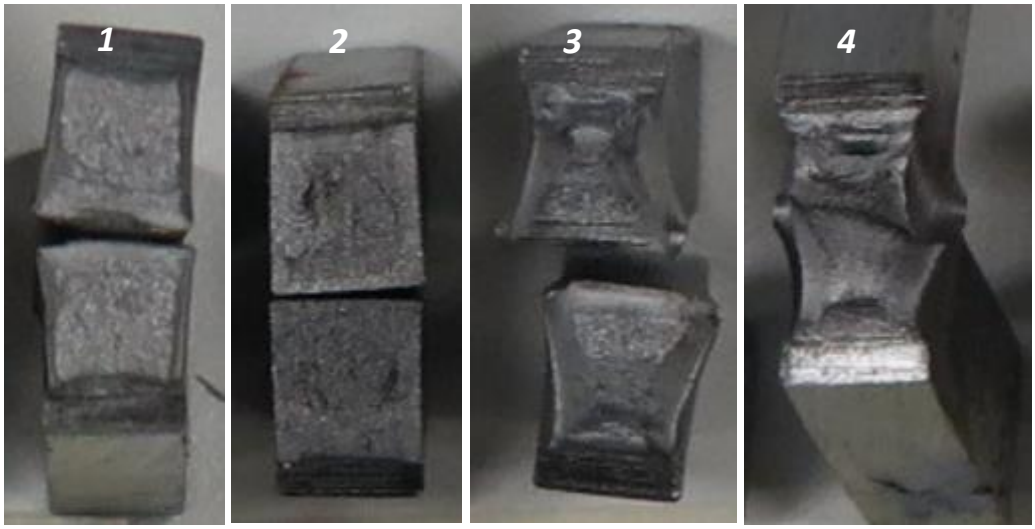
2.7.3.2. Exercise 2 | Demonstration

A. Calculate the elongation on the specimen you received; consider a starting width of the weld of 15 mm
B. measure the size of the specimen you received and define if it is in compliance with ISO 5173 and can be tested according to same standard test method
C. measure the angle at which the specimen you received was bent

2.7.4. Charpy Impact Strength Test of Metals and Welded Joints Exercises

2.7.4.1. Exercise 1

Re-arrange the following pictures of tested Charpy V-notch specimens from that tested at lower temperature up that tested at the higher temperature, list the reference numbers in the correct order. Than order the specimens from that with highest lateral expansion to that with the lowest.



Finally, try to estimate the range of the fracture shear area of each specimen with an error of the 5% (e.g. specimen X related to a shear area in the range 10÷20%).

2.7.4.2. Exercise 2 | Demonstration

A. measure the lateral expansion of the broken specimen you received
B. verify the dimension of the specimen you receive and confirm if the tolerances of ISO 148-1 are fulfilled

2.7.5. Fracture Tests of Welded Joints Exercises

2.7.5.1. Exercise 1

Describe where you would place the notch on these types of sample:

- carbon steel butt weld, 20 mm thick
- stainless steel butt weld, 25 mm thick

and define if the cooling of the specimen before the rupture is suggested to limit plastic deformations, therefore select one of the following options and explain your answer:

- cooling is suggested on both the samples (carbon steel and stainless steel)
- cooling is suggested just on carbon steel
- cooling is suggested just on stainless steel

2.7.5.2. Exercise 2 | Demonstration

A. identify and measure the imperfections of the specimens you received
B. identify the type of notch and calculate the examination area on the specimen you received

2.7.6. Hardness Tests of Welded Joints Exercises

2.7.6.1. Exercise 1

What are the steps before to measure the Vickers Hardness of a material?

1. Place the sample on the stage platform.
2. Move the sample into position.
3. Scroll to focus.
4. Select the test method and load.
5. Choose an objective and task name.
6. Use the overview camera to position the indenter.
7. Star the indenter test.

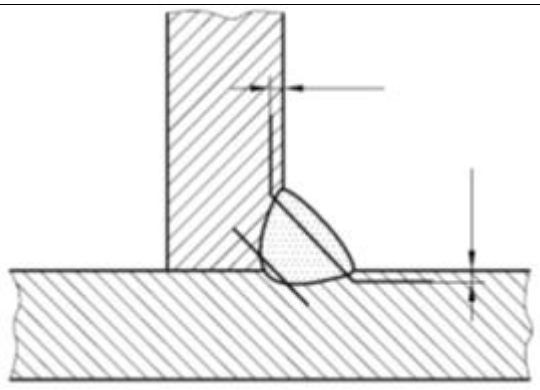
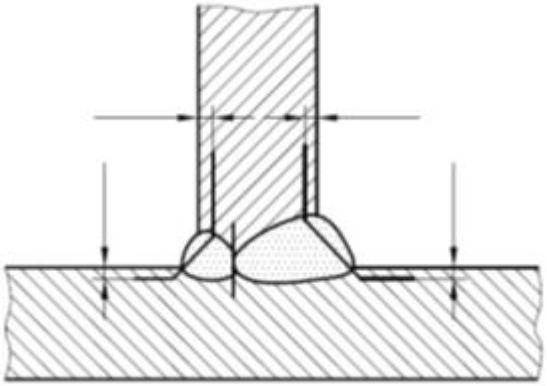
2.7.6.2. Exercise 2

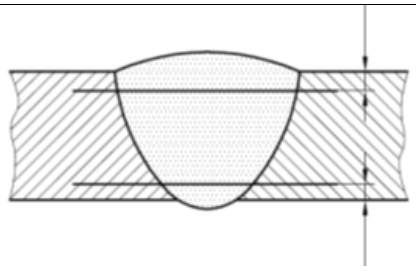
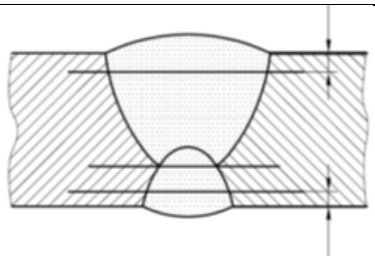
What surface condition is necessary for Vickers hardness test?

The required surface condition for the Vickers hardness test depends on the load used. For macro hardness testing, the loads applied must be higher than 1 kgf (HV1) and the surface should be ground. Generally a HV10 load is applied.

2.7.6.3. Exercise 3 | Demonstration

For the qualification a welding procedure (all welding positions), please mark the distance and the number of indentations were the hardness of the specimen shall be measured:

	
Fillet weld	**T-butt weld**

	
Butt weld from one side only both single and multirun	**Butt weld from both sides both single and multirun**

3. Measurement uncertainty

3.1. General methods of calculating uncertainties

No measurement is exact. When a value is measured, the outcome depends on the measuring system, the measurement procedure, the skill of the operator, the environment, and other effects.

Even if the quantity where to be measured several times, in the same way and in the same circumstances, a different measured value would in general be obtained each time, assuming the measuring system has sufficient resolution to distinguish between the values.

The dispersion of the measured values would relate to how well the measurement is performed. Their average would provide an estimate of the true value of the quantity that generally would be more reliable than an individual measured value. The dispersion and the number of measured values would provide information relating to the average value as an estimate of the true value. However, this information would not generally be adequate.

In metrology, **measurement uncertainty** is the expression of the statistical dispersion of the values attributed to a measured quantity. All measurements are subject to uncertainty and a measurement result is complete only when it is accompanied by a statement of the associated uncertainty, such as the standard deviation. By international agreement, this uncertainty has a probabilistic basis and reflects an incomplete knowledge of the quantity value.

The measurement uncertainty is often taken as the standard deviation of a state-of-knowledge probability distribution over the possible values that could be attributed to a measured quantity. Relative uncertainty is the measurement uncertainty relative to the magnitude of a particular single choice for the value for the measured quantity, when this choice is nonzero. This particular single choice is usually called the measured value, which may be optimal in some well-defined sense (e.g., a mean value). Thus, the relative measurement uncertainty is the measurement uncertainty divided by the absolute value of the measured value, when the measured value is not zero.

This uncertainty should be reported either as an explicit value ± or as an implied uncertainty using the appropriate number of significant figures.

The measurement uncertainty is:

- a parameter associated with the result of a measurement, which characterizes the dispersion of true values that could reasonably be attributed to the measurand [1].
- the doubt that exists regarding the result of any measurement [2].

- the expression of the statistical dispersion of the values assigned to a measured quantity [3].
- a complete evaluation of the uncertainty should be done according to JCGM 100:2008 [2]
- independent of the type of sources, for hardness, there are two possibilities for the determination of the uncertainty.
- one possibility is based on the evaluation of all relevant sources appearing during a direct calibration. As a reference, a Euramet guideline [3] is available;
- the other possibility is based on indirect calibration using a hardness reference block (CRM - certified reference material) [3, 4].

3.1.1. Error versus uncertainty

It is important not to confuse the terms "error" and "uncertainty".
Error is the difference between the measured value and the "true value" of the measured object.
Uncertainty is a quantification of the doubt about the result of the measurement.
Whenever possible, attempts are made to match any known errors: for example, by applying corrections from calibration certificates. But any error whose value is not known is a source of uncertainty.

3.1.2. The uncertainty and types of uncertainty

The ISO Guide approach to UM calculations:

- Specifications of the meter:
  - including the complete equation
- Quantification of significant uncertainties in all parameters:
  - A: from the statistics of the repeated experiment;
  - B: by any other means (theory, certificates, judgment...).
- Expressed as standard deviation;
- Combining according to the stated principles.

3.1.2.1. Standard deviation

Is the square root of Variant V = S^2

$$S^2 = \frac{\Sigma\,(x_i - \bar{x})^2}{n-1}$$

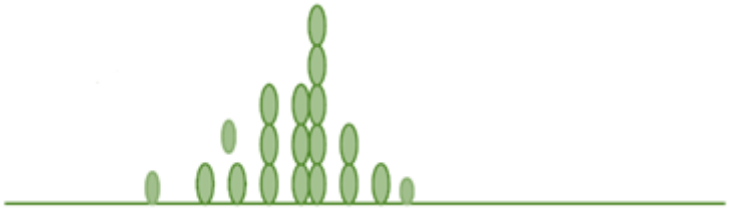


Figure 76 - Standard deviation histogram.

3.1.2.2. The standard uncertainty

Is the uncertainty of the result of a measurement expressed as standard deviation. Standard uncertainty is defined as one standard deviation.

$$S_{\bar{x}} = \frac{S}{\sqrt{n}}$$

All contributing uncertainties should be expressed at the same confidence level, converting them to standard uncertainties. A standard uncertainty is a margin whose size can be considered "plus or minus one standard deviation". The standard uncertainty tells us about the uncertainty of a mean (not just the spread of values). A standard uncertainty is usually denoted by the symbol u or u(y) (the standard uncertainty in y).

3.1.2.3. Type a uncertainty evaluation

Is the uncertainty evaluated through the statistical analysis of the series of observations.

From the repeated results: Uniform distribution = Normal distribution and standard uncertainty.

Normal distribution: It is used when making an estimate from repeated observations of a process that varies randomly.

An uncertainty is then given as a standard deviation.

Standard deviation of the mean (s/x mean): Relative standard deviation (RSD) or coefficient of variation %.

An uncertainty for a variable with a 95% confidence interval (or other) is given as:

- u(x) = k/2 (for 95% probability);
- u(x)= k/3 (for 99.7% probability).

Normal distribution: In a set of readings, values are sometimes more likely to fall close to the mean than further. This is typical of a normal (Gaussian) distribution. This type of distribution is distinguished

if the set of individuals is calculated from a large group of people. Most people are close to average height; few are extremely tall or short.

Figure 77 shows a set of 10 "random" values in an approximately normal distribution.

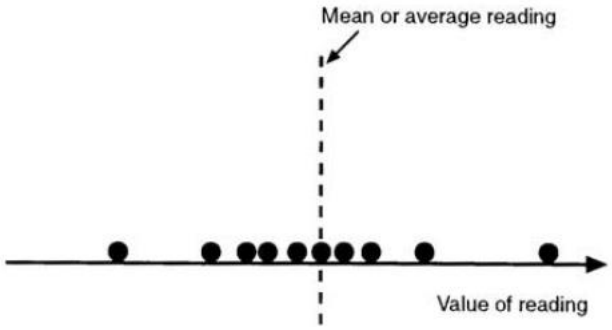


Figure 77 – "Blob plot" of a set of values lying in a normal distribution.

A sketch of a normal distribution is shown in Figure 78.

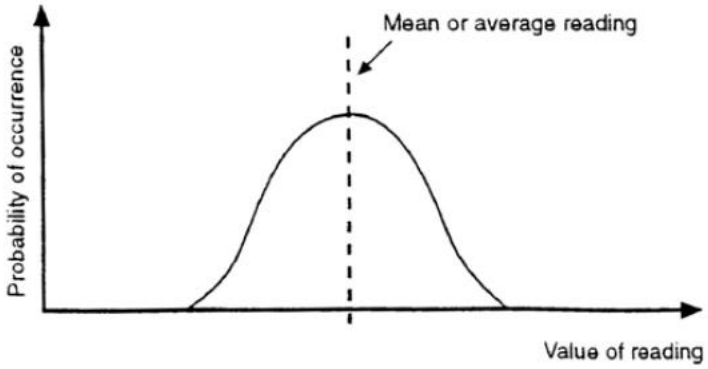


Figure 78 - Sketch of a "normal" distribution.

When a set of multiple repeated readings has been taken (for a Type A estimate of uncertainty), the mean, *x*, and the estimated standard deviation, *s*, can be calculated for the set. From these, the estimated standard uncertainty, *u*, of the mean is calculated from:

$$u = \frac{s}{\sqrt{n}}$$

Where:

- *n* – the number of measurements in the set. (The standard uncertainty of the mean has also been called the standard deviation of the mean or the standard error of the mean.)

3.1.2.4. Type B uncertainty assessment

Is uncertainty assessed by means other than statistical analysis of the series of observations.

From certificates and literature:

- Rectangular: Divisor: $\sqrt{3}$
- Triangular: Divisor: $\sqrt{6}$

Where information is sparser (in some B-type estimates), only the upper and lower bounds of uncertainty may be able to be estimated. It may then need to be estimated that the value is equally likely to fall anywhere in between, i.e. a rectangular or uniform distribution. The standard uncertainty for a **rectangular distribution** is calculated by:

$$\frac{a}{\sqrt{3}}$$

Where:

- a - half-range (or half-width) between the upper and lower limits.

Rectangular distributions occur quite frequently, but there may also be occasions where the use of the calculation formula is needed.

The rectangular distribution is used when information is taken from a certificate or specification, which gives the associated uncertainty without specifying the confidence level.

Example: The purity of cadmium is quoted as:

= 99.99 ± 0.1%.

These are cases of rectangular (uniform) distribution. In this method, the distributions are such that the probability of individual units (purity) is closer to the extremes. Therefore, an estimate is made by applying the rectangular distribution. So:

Assumed standard uncertainty = half width / Sq. $\sqrt{3}$

3.1.2.5. Combined uncertainty

The component uncertainties are combined to produce an overall uncertainty.

Individual standard uncertainties calculated by Type A or Type B evaluations can be validly combined by "summation of squares" (also known as "root sum of squares"). The result is called the combined standard uncertainty, denoted by u_c or $u_c(y)$.

Quadrature summation is simplest where the result of a measurement is achieved by addition or subtraction. More complicated cases are also covered below for multiplying and dividing measurements, as well as other functions.

- The component uncertainties are combined to produce an overall uncertainty;
- Some of the uncertainties may cancel each other out;
- Some may be interdependent;

- Type A and Type B uncertainty factors;
- When combining all factors, they must be converted to a similar unit of measure, (eg, %; gm; ml; ^{o}C; one less unit).

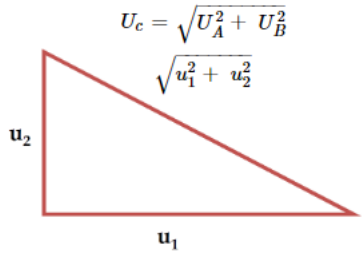


Figure 79 - Combining uncertainties.

3.1.2.6. Extended uncertainty

In some cases, the combined standard uncertainty must be multiplied by the appropriate coverage factor.

$$U_E = k \cdot U_c$$

where:

- *k* – normally 1.96 or 2.00 for a 95% confidence level.

3.2. Measurement uncertainty for tensile test, impact test, and hardness test

Measurement uncertainties can come from the measuring instrument, the measured item, the environment, the operator, and other sources. Such uncertainties can be estimated using statistical analysis of a set of measurements and using other types of information about the measurement process. There are established rules for how to calculate an overall estimate of uncertainty from this individual information. The use of good practices - such as traceable calibration, careful calculation, good record keeping and verification - can reduce measurement uncertainties.

When the uncertainty in a measurement is assessed and stated, the fitness for purpose of the measurement can be assessed accordingly.

Accuracy of Accuracy: The relationship between accuracy and precision can be illustrated by the familiar example of shooting a rifle at a target where the black dots below represent hits on the target.

Figure 80 - Precision accuracy.

Good precision does not necessarily mean good accuracy. However, if an instrument is well calibrated, the precision or reproducibility of the result is a good measure of its accuracy.

Since there is always a margin of doubt about any measurement, we must ask, "How big is the margin?" and "How serious is the doubt?" Thus, two numbers are really needed to quantify an uncertainty. One is the margin width or spacing. The other is a confidence level and states how certain we are that the "true value" lies within this range.

Example:

We could say that the length of a particular stick measures 20 cm plus/minus 1 cm, at the 95% confidence level. This result could be written:

20 cm ±1 cm, at a 95% confidence level

The statement says that we are 95% certain that the stick is between 19 and 21 cm long.

3.2.1. Determination of uncertainty in different fields

It is good practice in any measurement to evaluate and report the uncertainty associated with test results. An uncertainty statement may be requested by a customer who wishes to know the limits within which the reported result can be assumed to lie, or the test laboratory itself may wish to develop a better understanding of which particular aspects of the test procedure have the biggest effect on the results so that it can be more closely controlled.

Determination of measurement uncertainty can be done for:

- mechanical tests on metallic materials, determination of uncertainties during impact testing (Charpy hammer);
- mechanical tests on metallic materials, hardness measurements;
- mechanical tests on metallic materials, tensile uncertainty testing;
- conformity assessment activities;

3.2.1.1. Uncertainty in tensile testing

In any tensile measurement we must clearly and unambiguously state the measurand, meaning the final value of interest. Often this information regarding the measurand is acquired from reading a single measuring instrument.

Such a measurement is considered as being a direct measurement. However, the metrological meaning of the word “measurement” is larger. The word „measurement” also refers to quantities whose values are indirectly estimated on the basis of the values, which may, or not, have been directly measured.

In order to estimate the values of measurands, subject to an indirect measurement, a proper measurement model shall be established. The model should provide a realistic picture of the elements involved in the measurement. The model should be documented, generally in terms of one or more mathematical formulae or may be in the form of an algorithm.

Example. The modulus of elasticity (*E)* of a sheet metal is usually determined according to the following formula:

$$E = \sigma/\varepsilon$$

where:

- σ - stands for stress and ε for strain (ε = (L− Lo)/Lo, where Lo is the original distance between the marks and L is the final distance between the marks).

A prepared specimen is placed in a tensile testing machine. The machine will apply a load *L* that is measured directly with a transducer such as a load cell. At the same time, the distance between two marks on the stretched specimen is measured directly with an extensometer.

The stress value will be then:

$$\sigma = F/A,$$

where
F - applied force
A - cross section of the specimen.

The area is evaluated according to the model $A = ae$,
where:
a - width of the specimen
e - thickness (figure 81).

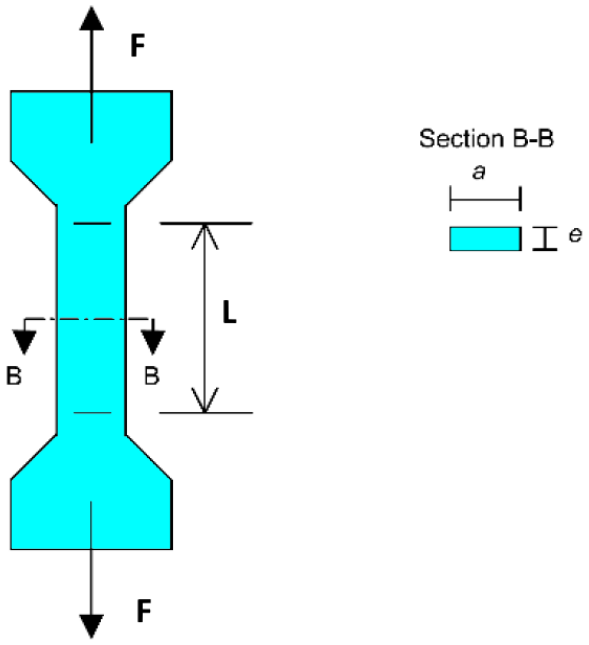


Figure 81 - Precision accuracy.

Thus, in this example the evaluation task has been broken down into sub-models, for which the quantities subject to direct measurement are *F*, L, *a* and *e*, while *A*, *σ* and *ε* are quantities that intermediate. There is also the possibility that we combine these sub-models in a single model whose input quantities are only those directly measured.

In general, the used measurement model should be considered as a black box, that takes in *input values* and produces *output values*. The primary input values need not be those directly measured by the evaluator (values that have been determined on a different occasion) or by other observers. The

output quantities are not necessarily the measurands of interest, because they may act as input quantities in the case of another model. For example, the modulus of elasticity *E value,* of a metal sheet may be required, for calculating the deformation of a beam under a specific load, and there may be no need to measure *E* if its value can be estimated from literature data. We refer to a quantity whose value is not estimated as part of the current evaluation task as an imported quantity. Even the simplest model will be incomplete if corrections to the indications of the instruments used in direct measurements are not taken into account.

Every directly measured quantity X should be modelled as X = A + B, where A is the value associated with the gauged indications of the instrument and B is a quantity that consists of one or more correction quantities.

Alternatively, one may write X = A x C, where C is a correction factor.

For example, if the input quantities *a* and *e* in the model *A* = *a x e,* have been measured with a common instrument, such as a caliper, the correction to its indications induces a correlation between *a* and *e*. Even if the value of this correction is taken as zero, its uncertainty will have an influence on the uncertainty associated with the estimate of *A*. A further complication of such a model, to be used, is due to the fact that some values may not appear explicitly in the model, even though they do modify the uncertainty value.

In order to achieve test results with a reduced measurement uncertainty, it is recommended that the original cross-sectional area be determined with an accuracy of ±1 % or better. For thin materials, special measurement techniques can be required.

There are two methods of testing speeds available. The first, method A, is based on strain rates (including crosshead separation rate) while the second, method B, is based on stress rates.

Note: Knowledge about a quantity can be inferred either from repeated measurements (called Type A estimation) or from scientific judgment based on all available information about the possible variability of the quantity (called Type B estimation).

Method A is intended to minimize the variation of the test rates during the moment when strain rate sensitive parameters are determined and to minimize the measurement uncertainty of the test results.

Therefore, and out of the fact that often the strain rate sensitivity of the materials is not known, the use of method A is strongly recommended.

When testing and calibration activities are performed outside the temperature limits of 10 °C and 35 °C, the temperature shall be recorded and reported. If significant temperature gradients are present during testing and/or calibration, the measurement uncertainty may increase and out of tolerance, conditions may occur.

Measurement uncertainty analysis is useful for identifying major sources of inconsistencies of measured results.

Product standards and material property databases based and/or related to ISO 6892 have an inherent contribution from measurement uncertainty. It is therefore inappropriate to apply further adjustments for measurement uncertainty and thereby risk failing product, which is compliant. For this reason, the estimates of uncertainty derived by following this procedure are for information only.
Note: The test conditions and limits defined in this document shall not be adjusted to take account of uncertainties of measurement and the estimated measurement uncertainties shall not be combined with measured results to assess conformance to product specifications.

Although ISO 6892-1 requires the generation of a straight line with a given offset parallel to the linear region of the stress-strain curve in order to determine the specified proof strength, Rp, of the material being tested, most users usually assume that the slope of the linear elastic region of the stress-strain curve corresponds to the modulus of elasticity of the material being tested since the modulus of elasticity, E, is given by the relationship E = stress/strain. However, in general, the Class 1 extensometer required for the tensile test is not sufficiently accurate for measuring the very small strains in the elastic region with sufficient precision to give modulus values with an acceptable level of uncertainty.

For consideration of uncertainty, see Annexes K and L of ISO 6892, which provide guidance for the determination of uncertainty related to metrological parameters and values obtained from the interlaboratory tests on a group of steels and aluminum alloys.

The estimation of the measurement uncertainty for a determined modulus of elasticity can be done according to CWA 15261-2:2005, A.5 or according to Annex K of ISO 6892.

Note: The estimation of the measurement uncertainty according to CWA 15261–2 is based on absolute values. This results in different estimations of the respective single uncertainty budgets, if e.g. the test piece dimensions or the extensometer gauge length differ. The estimation of the measurement uncertainty according to Annex K of ISO 6892is based on relative estimations. Therefore, the relative estimations normally will not change.

Exception is the relative measurement uncertainty budget for the strain measurement. Because of the small extensions during the test in the elastic part, the absolute uncertainty of the strain measurement is relevant for the uncertainty contribution (according to ISO 9513).

In CWA 15261–2, the symbol L_o is used for the gauge length and m_E for the slope of the elastic part of the force-extension curve. For to prevent confusion (differing from CWA), the symbol L_e is used for the extensometer gauge length and S_E for the slope of the elastic part of the force-extension curve. The measurement uncertainty according to CWA 15261-2 is given by formula below.

$$u_c(E) = \sqrt{\left(\frac{L_e}{S_o}\right)^2 \cdot u^2(S_E) + \left(\frac{S_E}{S_o}\right)^2 \cdot u^2(L_e) + \left(-\frac{S_E L_e}{S_o^2}\right)^2 \cdot u^2(S_o)}$$

Where:
L_e - extensometer gauge length;
S_o - original cross-sectional area;
S_E - slope of the force-extension curve;
$u(S_E)$ - uncertainty of slope of the force-extension curve;
$u(L_e)$ - uncertainty of extensometer gauge length;
$u(S_o)$ - uncertainty of original cross-sectional area.

Note: In case of reproducing the tests, the reproducibility values used in Tables 17 to 19 are half width intervals in accordance with ISO/IEC Guide 98-3 [7] and should be interpreted as the value of plus and minus [±] scatter tolerances.

The standard uncertainty; u, of the value of a parameter can be estimated in two ways.

a) Type A – By repeated measurement

$$\boldsymbol{u = \frac{s}{\sqrt{n}}}$$

where:
s – standard deviation of the measurements;

n – number of observations being averaged to report the result of the measurement under normal circumstances.

b) Type B – From some other source, e.g. calibration certificates or tolerances

The true value is equally likely to occur anywhere within the defined interval so the distribution is described as rectangular or uniform. Here the standard uncertainty is given by formula below.

$$u = \frac{a}{\sqrt{3}}$$

where:
a - half the width of the interval in which the quantity is assumed to lie;

Often the estimation of a value; *y* involves the measurement of other values. The estimation of the uncertainty in *y* shall take account of the contributions of the uncertainties in all these measurements. It is thus known as a combined uncertainty. If the estimation simply involves the addition or subtraction of a series of measurements, $x_1, x_2 \ldots x_n$, then the combined uncertainty in *y* $u(y)$, is given by formula below.

$$u(y) = \sqrt{(u(x_1)^2 + u(x_2)^2 + \cdots + u(x_n)^2)}$$

where:

$u(x_1)$ - uncertainty in the parameter x_1 etc.

Equipment parameters effect on the uncertainty of test results

The uncertainty of the results determined from a tensile test contains components due to the equipment used. Various test results have differing uncertainty contributions depending on the way they are determined. Table 17 indicates the equipment uncertainty contributions that should be considered for some of the more common material properties determined in a tensile test. Some of the test results can be determined with a lower uncertainty than others, e.g. the upper yield strength, R_{eH}, is only dependent on the uncertainties of measurement of force and cross-sectional area, while proof strength, R_p, is dependent on force, extension, gauge length, cross-sectional area, and other parameters. For reduction of area, Z, the measurement uncertainties of cross-sectional area both before and after fracture need to be considered.

Parameter	Test results					
	R_{eH}	R_{eL}	R_m	R_p	A	Z
Force	X	X	X	X	—	—
Extension	—	—	—	X	X	—
Gauge length	—	—	—	X	X	—
S_o	X	X	X	X	—	X
S_u	—	—	—	—	—	X
X Relevant. — Not relevant.						

Table 17 - Uncertainty contributors to the test results, due to the measuring devices.

The uncertainty of the test results listed in Table 17 may be derived from the calibration certificates of the devices used for the determination of the test results. The uncertainty can be significantly higher or lower, and the equipment certificate should be consulted. Uncertainty contributions due to factors such as drift of the equipment since its calibration and its use in different environmental conditions should also be taken into account.

Parameters depending on the material and/or the test procedure

The precision of the test results from a tensile test is dependent upon factors related to the material being tested, the testing machine, the test procedure and the methods used to calculate the specified material properties. Ideally, all the following factors should be considered:

a. test temperature;
b. testing rates;
c. the test piece geometry and machining;
d. the method of gripping the test piece and the axiality of the application of the force;
e. the testing machine characteristics (stiffness, drive and control mode);
f. human and software errors associated with the determination of the tensile properties;
g. extensometer mounting geometry.

The influence of these factors depends on specific material behavior and cannot be given as a defined value. If the influence is known, it can be taken into account in the calculation of the uncertainty. It can be possible to include further sources of uncertainty in the estimation of the expanded measurement uncertainty. This can be done using the following approach.

a. The user has to identify all additional possible sources, which can have an effect, directly or indirectly on the test parameter to be determined.

b. Relative contributions may vary according to the material tested and the special test conditions.

Individual laboratories are encouraged to prepare a list of possible sources of uncertainty and evaluate their influence on the result. If a significant influence was determined, this uncertainty; u_p has to be included in the calculation. The uncertainty; u_p is the uncertainty of the source *i* on the value to be determined as a percentage as shown in Formula 10. For u_i, the distribution function of the specific parameter (normal, rectangular, etc.) has to be identified. Then the influence on the result on the one sigma level has to be determined. This is the standard uncertainty.

Interlaboratory tests may be used to determine the overall uncertainty of results under conditions close to those used at industrial laboratories, but such tests do not separate effects related to the material inhomogeneity from those attributable to the testing method.

It should be appreciated that as suitable certified reference materials become available, they will offer a useful means of estimating the measurement uncertainty on any given testing machine including the influence of grips, bending, etc., which at present are difficult to quantify.

Alternatively, it is recommended that regular in-house tests be carried out for quality control purposes on material with a low level of scatter in properties (non-certified reference materials) [18].

There are some examples for which it is very difficult to give accurate uncertainty values without reference materials. When reliable uncertainty values are important, in some cases, the use of a certified reference material or non-certified reference material to confirm uncertainty of measurements is recommended.
The following procedure will detail the steps for uncertainty estimation related to the uncertainty in tensile tests.

The assessment of uncertainty associated with test (or calibration) results is based on the following basic concepts:

- knowledge about any quantity that influences the outcome of a measurement is in principle incomplete and can be expressed by a probability density function (pdf) of the quantity's probable values.

- the average of the probability density is considered the best estimate of the value of the quantity. The standard deviation of the probability density is taken as the standard uncertainty in determining the value of the quantity.
- knowledge about a quantity (Type A or B estimation).

Uncertainty in the measurement of a dimension of a tensile test specimen will influence the measurement of tensile strength because the dimensions are needed to calculate the stress. This is known as uncertainty propagation, which is again a central concept for uncertainty estimation.

A model for the propagation of uncertainties needs to be determined and used to calculate the combined uncertainty of parameters such as tensile strength. In mechanical testing, linearized models are mostly found to apply, and a root-sum-square derivation can be applied to calculate the uncertainty associated with a measurand (output quantity) from the uncertainties of various influencing measurements (input quantities). each appropriately weighted by sensitivity coefficients.

The uncertainty estimation procedure, with special reference to mechanical tests, can be said to consist of the following steps:

1. Identification of the parameters for which the uncertainty is to be estimated;
2. Identification of all sources of uncertainty in the test;
3. Classification of uncertainty in Type A and B;
4. Estimation of the standard uncertainty for each source of uncertainty;
5. Calculation of the combined uncertainty for the parameters identified at 1);
6. Calculation of extended uncertainty;
7. Reporting results.

Tensile testing is one of the most common mechanical tests performed to quantify the stiffness, strength, and ductility properties of materials.

Essentially, the tensile test consists of loading, at a constant rate of displacement or strain, a specimen, providing a length (gage) of material of uniform cross-section, to rupture. The force (more commonly called the load) experienced by the specimen and the extension of the gauge length are monitored during the test to calculate the various characteristic properties of the material. Typically, specimens have a rectangular or circular cross-section in the gauge region. The engineering stress experienced by the material in the gage region at any time during the test is obtained by dividing the force exerted

on the specimen by the initial cross-sectional area of the gage. The appropriate engineering tension is given by the ratio of the extension to the gauge to the initial gauge length.

Step 1. Identifying the parameters for which the uncertainty is to be estimated.
Almost always in mechanical testing, the measurements (output quantities) characterizing the material properties cannot be obtained directly, but must be calculated from measurements (input quantities) obtained from the specimens and those made during the test.

Step 2. Identify all sources of uncertainty in the test.
For the tensile test, the major sources of uncertainty have to be classified. The established categories may change. with the material tested and the test conditions.

Step 3. Classification of uncertainty according to type A or B.
For mechanical tests, the sources of uncertainties are mostly type B, as they can be quantified from already available data.

Some of the sources of uncertainty can be directly related to the primary measurements taken during a mechanical test, therefore directly affecting the quality of the measurements. However, other factors may also affect its quality. Other factors such as surface roughness, sample size and room temperature have a weak influence on $s_{0.2\%}$.

Step 4. Estimate the standard uncertainty for each source of uncertainty.
The standard uncertainty is related to the standard deviation of the value associated with the measurement.

If the uncertainty is of type A, that is, a number of measurements of the quantity where made to obtain the pdf, and the standard deviation of the distribution was calculated to be s , then the uncertainty is given by $u=st(P,f)$, where $t(P,f)$ is a factor obtained from the Students distribution for the confidence level P (typically 68.27%) and (n-1) degrees of freedom, n being the number of measuremets taken.

If the uncertainty is of type B, a rectangular distribution can be assumed. For example, if the accuracy of a dimension measuring device is known to be x and a dimension of y *is measured,* then the actual value of the dimension can be anywhere in the range $y \pm x$. The uncertainty in this case is given by $u=x$.

Step 5. Calculation of the combined uncertainty u_c

This is usually the most difficult element in the process of estimating the uncertainties of mechanical test results. It is based on the cause-effect relationship that links the result of measurements to the measurand.

$$u_c(y) = \sqrt{\sum_{i=1}^{N} [c_i \cdot u(x_i)]^2}$$

where:
x_i - the sensitivity coefficient associated with x_i.

Such a model assumes that the individual sources of uncertainty are uncorrelated.
The sensitivity coefficient *c* can be obtained from the functional relationship of the measurand to the measurements, wherever such relationships exist.

Depending on the tensile strength of the test temperature, it is imperative that empirical relationships be developed in the long term, although these may be limited to only one class of material or a defined temperature range.

The application of the combined uncertainty equation is best understood by using it for the specific case of tensile testing. For a test specimen of rectangular cross-section, the initial area is given in terms of width and breadth by:

$$A_0 = a_0 \cdot b_0$$

The sensitivity coefficients associated with a_o and b_o are given by:

$$c_{a0} = b_0 \text{ and } c_{b0} = a_0$$

and the uncertainty in A_o can be expressed by u_{A0}=

where:

u_{a0} and u_{b0} - the individual uncertainties in the measurement of a_o and b_o.

Since a derivation of the combined uncertainty of the various measurements in a tensile test can be quite involved, the final form of some of the more commonly required output quantities is summarized in Table of the standard.

In relation to the derivation of the combined uncertainties, if a mathematical model for the test is missing, laboratories can list those quantities and parameters that may have a relevant influence on the uncertainty and attempt to estimate their contribution to the overall uncertainty.

Step 6. Calculation of the expanded uncertainty *U.*

Expanded uncertainty, *Uc*, is defined as "the range about the result of a measurement that can be expected to encompass a large part of the distribution of values that could reasonably be assigned to the measurand". It is obtained by multiplying the combined uncertainty, u_c, by a coverage factor, *k*, which is selected based on the required confidence level.

For a normal probability distribution, the most commonly used coverage factor is 2, which corresponds to a 95.4% confidence interval (actually 95% for most practical purposes). The expanded uncertainty, *U,* is therefore wider than the combined uncertainty, u_c.

Step 7. Reporting the results.

Once the expanded uncertainty has been estimated, the results should be reported as follows:

$$V = y \pm U$$

where:

V - estimated value of the measurand,

y - average result of the test (or measurement),

U - expanded uncertainty associated with *y*.

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor, *k = 2*, which for a normal distribution corresponds to a coverage probability, *p*, of approximately 95 %.

3.2.1.2. Uncertainty in Charpy testing

ISO 148-1 specifies in the Annex a method for determining the uncertainty, u (KV), associated with the mean absorbed energy, KV, of a set of specimens of a test material. Other methods of assessing u (KV) can be developed, if they meet the requirements of the GUM.

This approach requires input from the “indirect verification” of the Charpy pendulum impact testing machine, which is a normative method of assessing the performance of the instrument with reference test pieces (see ISO 148-2).

Note: The ISO 148 series requires Charpy pendulum impact testing machines to successfully meet the requirements for both indirect and direct verification. The latter consists of a check of all individual geometric and mechanical requirements imposed on the construction of the instrument (see ISO 148-2).

The roles of direct and indirect verification in the metrological traceability chain of Charpy measurements are given in Figure 82. The chain starts at the international level with the definition of the measurand, *KV,* or absorbed energy, in the standard procedures described in the ISO 148 series.

Calibration laboratories use the certified reference test pieces to verify their reference machine and can use their pendulum to characterize and produce reference test pieces. At the user level, Charpy test laboratories can verify their pendulum with reference test pieces to obtain reliable *KV* values.

Note: Users can choose to acquire certified reference test pieces from national or international organizations, by-passing the calibration laboratory level.

Measurement uncertainty analysis is useful in identifying major sources of inconsistencies in measured results.

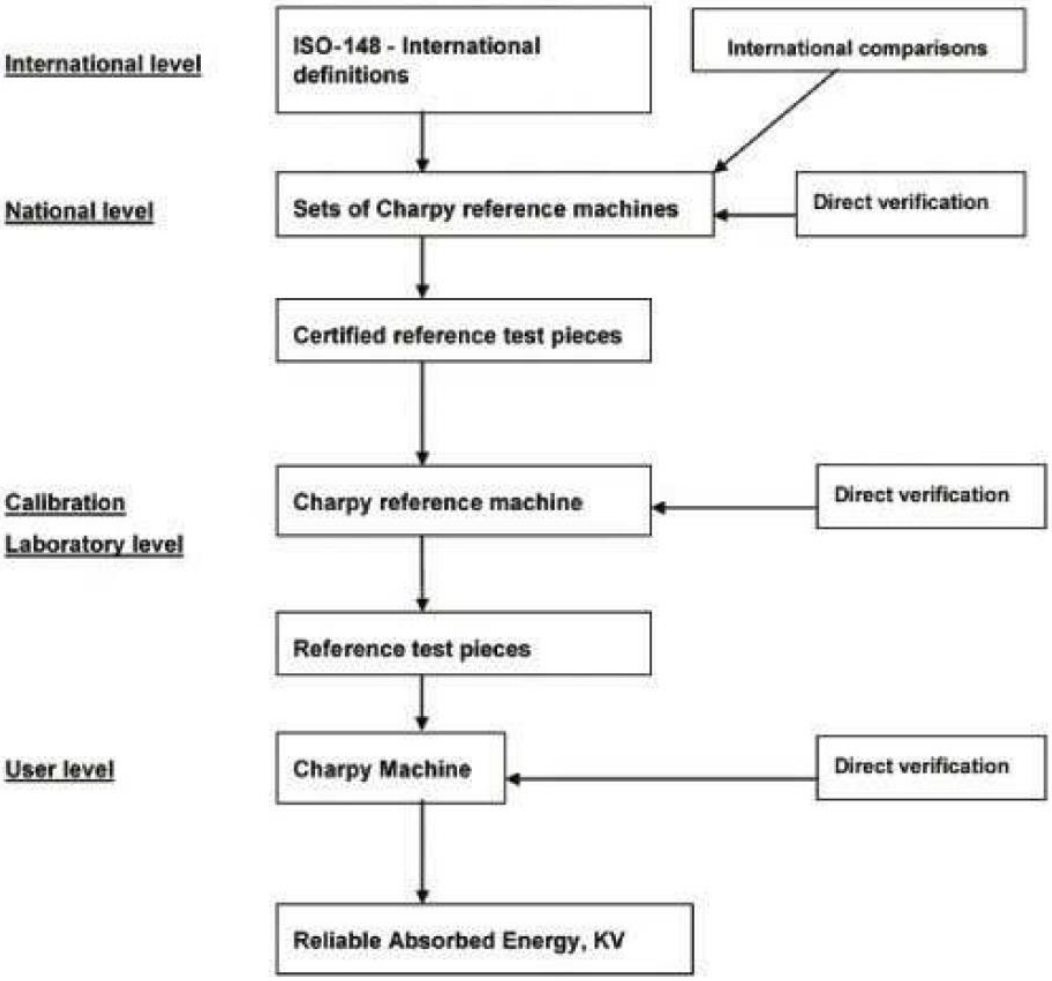


Figure 82 - Structure of the metrological traceability chain for the definition and dissemination of the absorbed energy scales of the Charpy impact test.

Product standards and material property databases based on this part of ISO 148 have an inherent contribution from measurement uncertainty. It is therefore inappropriate to apply further adjustments for measurement uncertainty and thereby risk a product which fails compliance. For this reason, the estimates of uncertainty derived from following this procedure are for information only, unless specifically instructed otherwise by the customer.

The test conditions and limits defined in this part of ISO 148 should not be adjusted to take account of uncertainties of measurement, unless specifically instructed otherwise by the customer. The estimated measurement uncertainties should not be combined with measured results to assess compliance to product specifications, unless specifically instructed otherwise by the customer. Instead, the indicated tolerances are to be interpreted as acceptance intervals. This approach assumes that measurements are made with a tacitly accepted maximum measurement uncertainty. Where possible, this maximum measurement uncertainty has been specified in the current version of the ISO 148 series. Measurement uncertainties of the measured values should be smaller than the indicated values.

Factors contributing to uncertainty

The principal factors contributing to uncertainty are associated with:

a. machine bias deduced from the indirect verification,

b. homogeneity of the test material and machine repeatability;

c. test temperature.

The measurement equation for the mean absorbed energy *KV* is formula below.

$$\overline{KV} = \bar{x} - B_V - T_x$$

Where:

x – observed mean absorbed energy of n test specimens;

B_v - instrument bias based on the indirect verification;

T_x - bias due to temperature.

As a rule [18], measured values should be corrected for known bias. Indirect verification is one way to establish the value of bias. The machine bias determined by indirect verification is defined in ISO 148-2, as given in formula below.

$$B_V = \overline{KV_V} - KV_R$$

Where:

KV_V – mean value of the reference test pieces broken during the indirect verification;

KV_R - certified value of the reference test pieces;

Depending on how well the value of B_V is known, different actions are proposed in ISO 148-2 which deals with the uncertainty associated with the results of indirect verification.

a. *By* is well known and stable. In this exceptional case, the observed value *x* is corrected by a term equal to *By* to obtain *KV.*

b. Most often, there is no firm evidence about the stability of the value of B_V. In this case, the bias is not corrected for, but it contributes to u_V, the uncertainty of the indirect verification result.

In both cases, an uncertainty; u_V, associated with the indirect verification result and the machine bias is calculated in accordance with procedures described in ISO 148-2. The outcome of the uncertainty analysis of the indirect verification is the value u_V.

If there is a significant difference between the values of KV_V and *KV,* then the values B_V and u_V should be multiplied by the ratio KV/KV_V.

Machine repeatability and material heterogeneity

The uncertainty of *x,* the mean observed absorbed energy of *n* test specimens, is determined using formula below.

$$u(\bar{x}) = \frac{s_x}{\sqrt{n}}$$

where:

s_x - standard deviation of the values obtained on the *n* test samples.

The value s_x is caused by two factors:
- machine repeatability;
- sample-to-sample material heterogeneity.

These factors are confounded, and therefore, are both included in this term. It is recommended to report the total measurement uncertainty with the value of s_x as a conservative measure for the variation in K_V *due* to material heterogeneity.

The value of v_x, the number of degrees of freedom of *u(x)*, is calculated as *n-1*.

Temperature bias

The effect of temperature bias, T_X, on the absorbed energy is extremely material dependent. If steel is tested in the brittle-to-ductile transition region, small changes in temperature can correspond to large differences in absorbed energy. At the time of publication, it is not possible to present a generic and accepted approach to the calculation of the contribution to absorbed energy uncertainty corresponding with the uncertainty of the measured test temperature. Instead, it is proposed to complement the statement of the measurement uncertainty in terms of absorbed energy with a separate statement on u_T, the uncertainty of the test temperature at which the absorbed energy was measured.

Machine resolution

The effect of machine resolution is in most cases negligible in comparison with the other factors contributing to uncertainty. An exception is the case where machine resolution is large, and the measured energy is low. In that case, the corresponding uncertainty contribution is calculated using formula below.

$$u(r) = \frac{r}{\sqrt{3}}$$

where:

r - machine resolution

The corresponding number of degrees of freedom is ∞.

Combined and expanded uncertainty

To calculate *u(KV),* the factors contributing to uncertainty should be combined. Since u_T is treated separately, and since the terms *u(x)*, u_V and $u_{(r)}$ are independent of each other, the combined standard uncertainty is determined using formula below.

$$u(\overline{KV}) = \sqrt{u^2(\bar{x}) + u_V^2} + u^2(r)$$

As a general rule: a procedure to estimate the uncertainty in Charpy impact test energy must follow few steps.

Step 1. Identifying the parameters for which the uncertainty is to be estimated.

The first step is to list the quantities (measurements) for which the uncertainties must be calculated. Often intermediate measurements are recorded by the laboratory but not necessarily reported to the customer.

Step 2. Identify all sources of uncertainty in the test.

In step 2, the user must identify all possible sources of uncertainty that may have an effect (directly or indirectly) on the test. The list cannot be comprehensively identified in advance as it is uniquely associated with the individual test procedure and apparatus used.

This means that a new list must be prepared each time a particular test parameter changes (for example, when a plotter is replaced by a computer).

In the case of measuring the absorbed energy from the impact test it is very difficult to calculate the influence of each source of uncertainty. Approaching calibration by using a certified reference material (CRM) and taking into account precision errors, CRM repeatability, and test sample repeatability is generally the best approach. For the indirect verification of a Charpy impact machine, 10 tests (5 x 2 sets of samples) should be performed periodically using a single CRM. However, for a laboratory performing impact tests on a range of alloys, several material strength classes must be considered.

Other measurements can be carried out to verify that the dimensions of the specimen and the temperature fall within the tolerance limits. If they are not, these measurements are not used to correct the energy values, but it is reported that:

- the measured impact energy is measured on a specimen of different dimensions;
- the measured impact energy is measured at a different temperature.

To simplify the calculations, it is recommended to group the significant sources of uncertainty, in the following categories:

1. Charpy input energy due to test piece and notch geometry;
2. Uncertainty in the test system;
3. Uncertainty in the environment;
4. Uncertainty in the test procedure.

Step 3. Classification of uncertainty according to type A or B.

In the third step, sources of uncertainty are classified as type A or B, depending on how their influence is quantified. If the uncertainty is evaluated by statistical means (from a number of repeated observations), it is classified as type A, if it is evaluated by any other means, it should be classified as type B.

Values associated with type B uncertainties can be obtained from a number of sources, including a calibration certificate, manufacturer's information, or an expert's estimate. For type B uncertainties, the user is required to estimate the most appropriate probability distribution for each source.

Step 4. Estimate the standard uncertainty for each source of uncertainty.

In this step the standard uncertainty, is estimated for each input source identified. The standard uncertainty is defined as a standard deviation and is derived from the uncertainty of the input quantity divided by the parameter, d_v, associated with the assumed probability distribution. Divisors for the typical distributions most likely to be encountered are given.

The individual influences of each source of uncertainty on the absorbed energy are very complex and impractical. The easiest way is to use a CRM to calibrate the entire system and consider errors, CRM repeatability, and test sample repeatability.

Step 5. Calculation of the combined uncertainty u_c

Assuming that the individual sources of uncertainty are uncorrelated, the combined uncertainty of the measurand, $u_c(y)$, can be calculated using the root of the square sum:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} [c_i \cdot u(x_i)]^2}$$

where:

$_{xi}$ - the sensitivity coefficient associated with x_i.

This uncertainty corresponds to plus or minus one standard deviation on the law of normal distribution representing the studied quantity.

Step 6. Calculation of the expanded uncertainty *U.*

Expanded uncertainty, *U*, is defined as "the range about the result of a measurement that can be expected to encompass a large part of the distribution of values that could reasonably be assigned to the measurand ". It is obtained by multiplying the combined uncertainty, u_c, by a coverage factor, *k* , which is selected based on the required confidence level.

For a normal probability distribution, the most commonly used coverage factor is 2, which corresponds to a 95.4% confidence interval (actually 95% for most practical purposes). The expanded uncertainty, *U*, is therefore wider than the combined uncertainty, u_c.

Where the customer requires a higher confidence level (such as for aerospace, electronics, etc.), a coverage factor of 3 is used so that the corresponding confidence level increases to 99.73%.

In cases where the probability distribution of u_c is not normal or where the number of data points used in type A analysis is small, the value of *k* should be calculated from the degrees of freedom given by the Welsh-Satterthwaite method.

Step 7. Reporting the results.

Once the expanded uncertainty has been estimated, the results should be reported as follows:

$$V = y \pm U$$

where:

V - estimated value of the measurand,

y - average result of the test (or measurement),

U - expanded uncertainty associated with *y*.

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor, *k = 2*, which for a normal distribution corresponds to a coverage probability, of approximately 95%.

3.2.1.3. Uncertainty in bending test

A procedure for estimating uncertainty in hardness measurement by the indirect calibration method, there are several steps to follow.

Step 1. Identifying the parameters for which the uncertainty is to be estimated.
The first step is to list the quantities (measurements) for which the uncertainties must be calculated which are presented in table 17, which presents the parameters that are usually reported in hardness measurements by the indirect calibration method. None of these measurements are measured directly, but are determined from other quantities (or measurements).

Step 2. Identify all sources of uncertainty in the test.
In step 2, the user must identify all possible sources of uncertainty that may have an effect (directly or indirectly) on the test. The list cannot be comprehensively identified in advance as it is uniquely associated with the individual test procedure and apparatus used.

This procedure needs to include estimations related to the following sources, using the indirect calibration method:

- Uncertainty due to calibration of reference blocks;
- The uncertainty of the maximum admissible error according to the standards;
- Uncertainty due to repeatability under certain test conditions;

Step 3. Classification of uncertainty according to type A or B.
In the third step, sources of uncertainty are classified as type A or B, depending on how their influence is quantified. If the uncertainty is evaluated by statistical means (from a number of repeated observations), it is classified as type A, if it is evaluated by any other means, it should be classified as type B.

Values associated with type B uncertainties can be obtained from a number of sources, including a calibration certificate, manufacturer's information, or an expert's estimate. For type B uncertainties, the user is required to estimate for each source the most appropriate probability distribution.

Step 4. Estimate the standard uncertainty for each source of uncertainty.
In this step the standard uncertainty, u, is estimated for each identified input source. The standard uncertainty is defined as a standard deviation and is derived from the uncertainty of the input quantity

divided by the parameter, d_v, associated with the assumed probability distribution. Divisors for the typical distributions most likely to be encountered are given.

In many cases, the input quantity of the measurement may not be in the same units as the output quantity. For example, one contribution to hardness is surface roughness. In this case the input quantity is the roughness (mm) but the output quantity is the hardness which is HRB. In such a case, a sensitivity coefficient is used to convert from roughness to HRB.

Step 5. Calculation of the combined uncertainty u_c

Assuming that the individual sources of uncertainty are uncorrelated, the combined uncertainty of the measurand, $u_c(y)$, can be calculated using the root of the square sum:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} [c_i \cdot u(x_i)]^2}$$

where:

$_{xi}$ - the sensitivity coefficient associated with x_i.

This uncertainty corresponds to plus or minus one standard deviation on the law of normal distribution representing the studied quantity.

The combined uncertainty has an associated confidence level of 68.26%.

Step 6. Calculation of the expanded uncertainty *U.*

The expanded uncertainty, *U*, is defined as "the range about the result of a measurement that can be expected to encompass a large part of the distribution of values that could reasonably be assigned to the measurand ". It is obtained by multiplying the combined uncertainty, u_c, by a coverage factor, *k*, which is selected based on the required confidence level.

For a normal probability distribution, the most commonly used coverage factor is 2, which corresponds to a 95.4% confidence interval (actually 95% for most practical purposes). The expanded uncertainty, *U*, is therefore wider than the combined uncertainty, u_c.

Where the customer requires a higher confidence level (such as for aerospace, electronics, etc.), a coverage factor of 3 is used so that the corresponding confidence level increases to 99.73%.

In cases where the probability distribution of u_c is not normal or where the number of data points used in type A analysis is small, the value of *k* should be calculated from the degrees of freedom given by the Welsh-Satterthwaite method.

Step 7. Reporting the results.

Once the expanded uncertainty has been estimated, the results should be reported as follows:

$$V = y \pm U$$

Where:

V - estimated value of the measurand,

y - average result of the test (or measurement),

U - expanded uncertainty associated with *y*.

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor, *k = 2*, which for a normal distribution corresponds to a coverage probability, *p* , of approximately 95%.

3.2.1.4. Uncertainty in hardness testing

Independent of the type of sources, for hardness, there are two possibilities for the determination of the uncertainty.

- One possibility is based on the evaluation of all relevant sources appearing during a direct calibration. As a reference, a Euramet guideline [3] is available;
- The other possibility is based on indirect calibration using a hardness reference block (CRM - certified reference material) [3, 4]. A guideline for the determination is given in Annex D of ISO 6507-1.

It may not always be possible to quantify all the identified contributions to the uncertainty. In this case, an estimate of type A standard uncertainty may be obtained from the statistical analysis of repeated indentations into the test piece. Care should be taken, if standard uncertainties of type A and B are summarized, that the contributions are not counted twice (JCGM 100:2008, Clause 4).

When determining a specific tolerance that the machine needs to meet, the uncertainty associated with the use of measuring equipment and/or reference standards has been incorporated within this tolerance and it would therefore be inappropriate to make any further allowance for this uncertainty

by, for example, reducing the tolerance by the measurement uncertainty. This applies to all measurements made when performing a periodic verification of the machine.

The procedure calculates a combined uncertainty, u_H, by the Root-Squared-Sum-Method (RSS) out of the different sources (Table 18 - contains all symbols and their designation). The expanded uncertainty, U, is derived from u_H by multiplying with the coverage factor k = 2.

The bias, b, of a hardness testing machine (also named “error”), which is derived from the difference between:
- the certified calibration value of the hardness reference block used;
- the mean hardness value of the five indentations made in this block during calibration of the hardness testing machine (ISO 6507-2) can be implemented in different ways into the determination of uncertainty.

Two methods are given for determining the uncertainty of hardness measurements:
- Method M1 accounts for the systematic bias of the hardness machine in two different ways. In one approach, the uncertainty contribution from the systematic bias is added arithmetically to this value. In the other approach, a correction is made to the measurement result to compensate for the systematic bias.
- Method M2 allows the determination of uncertainty without having to consider the magnitude of the systematic bias [2, 3].

In hardness testing standards, certified reference material is equivalent to the hardness reference block, i.e. a piece of material with a certified value and associated uncertainty.

Procedures for calculating uncertainty: Hardness measurement values

A. Procedure with bias (method M1)

The method M1 procedure for the determination of measurement uncertainty is explained in Table 17.

The measurement bias, *b*, of the hardness testing machine can be expected to be a systematic effect. In JCGM 100:2008[2], it is recommended that a correction be used to compensate for systematic effects, and this is the basis of M1. The result of using this method is that either all determined hardness

values, *x*, have to be reduced by *b* or the uncertainty, *U*, has to be increased by *b*. The procedure for the determination of U_{M1} is explained in Table 18.

Step	Sources of uncertainty	Symbols	Formula	Literature/certificate	Example
1 M1,M2	Measurement result	x			$x = 410$ HV 30
2 M1	Bias value, b, and uncertainty, U_{HTM}, of the bias of the hardness testing machine from the indirect verification	b U_{HTM} u_{HTM}	$u_{HTM} = \frac{U_{HTM}}{2}$	b and U_{HTM} according to an indirect verification report using a CRM of $\bar{H}_{CRM} = 401,6$ HV 30 (see NOTE 1)	$b = 1,62$ HV 30 $U_{HTM} = 5,14$ HV 30 $u_{HTM} = \frac{5,14}{2} = 2,57$ HV 30
3 M2	Maximum permissible deviation of the bias	b_E	b_E = Maximum positive value of permissible bias	Permissible bias, b, according to ISO 6507-2:2017, Table 5	$b_E = 3$ % $b_E = \frac{3 \times 410}{100} = 12,3$ HV 30
4 M2	Standard uncertainty due to the maximum permissible deviation of the bias	u_E	$u_E = b_E / \sqrt{3}$	Rectangular distribution	$u_E = \frac{12,3}{\sqrt{3}} = 7,10$ HV 30
5 M1,M2	The standard deviation of repeatability measurements	s_H	$s_H = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(H_i - \bar{H})^2}$	Five measurements are made by the laboratory on a CRM having a hardness similar to the test sample (see NOTE 2)	$s_H = 3,2$ HV 30
6 M1,M2	Standard uncertainty due to lack of repeatability	U_H	$u_H = t \times s_H$	$t = 1,14$ for $n = 5$ (see JCGM 100:2008)	$u_H = 1,14 \times 3,2 = 3,69$ HV 30
7 M1,M2	Standard uncertainty due to resolution of the hardness value indicating display	u_{ms}	$u_{ms} = -\frac{2x}{d} \times \frac{\delta_{ms}}{2\sqrt{3}}$	$\delta_{ms} = 0,000\,51$ mm $x = 410$ HV 30 $d = 0,368\,4$ mm (see NOTE 3)	$u_{ms} = -\frac{2 \times 410,0}{0,368\,4} \times \frac{0,000\,51}{2 \times \sqrt{3}} = -0,33$ HV 30

Table 18 - Determination of the expanded uncertainly according to methods M1 and M2.

The combined expanded measurement uncertainty for a single hardness measurement, *x*, is calculated according to formula below.

$$U_{M1} = k \cdot \sqrt{u_H^2 + 2 \cdot u_{ms}^2 + u_{HTM}^2}$$

where:

u_H - contribution to the measurement uncertainty due to the lack of measurement repeatability of the hardness testing machine;

*u*ms - contribution to the measurement uncertainty due to the resolution of the hardness testing ma chine. Both the resolution of the length measurement indicating instrument and the optical resolution of the measuring microscope shall be considered. In most cases, the overall resolution of the measurement system should be included twice in the calculation of u_H due to resolving the positions of both ends of the diagonal independently;

u_{HTM} - contribution to the measurement uncertainty due to the standard uncertainty of the bias measurement, *b*, generated by the hardness testing machine (this value is reported as a result of the indirect verification defined in ISO 6507-2) and is defined according to formula below.

$$u_{HTM} = \sqrt{u_{CRM}^2 + u_{HCRM}^2 + u_{ms}^2}$$

where:

u_{CRM} - contribution to the measurement uncertainty due to the calibration uncertainty of the certified value of the CRM according to the calibration certificate for k = 1;

u_{HCRM} - contribution to the measurement uncertainty due to the combination of the lack of measurement repeatability of the hardness testing machine and the hardness nonuniformity of the CRM, calculated as the standard deviation of the mean of the hardness measurements when measuring the CRM;

u_{ms} - contribution to the measurement uncertainty due to the resolution of the hardness testing machine when measuring the CRM.

The result of the measurement can be reported in two ways:

- as X_{corr}, where the measurement value, x, is corrected for the measurement bias, b, calculated according to formula below.

$$\boldsymbol{X_{corr} = (x - b) \pm U_{M1}}$$

- as Xu_{corr}, where the measurement value, x, is not corrected for the measurement bias, b, and the expanded uncertainty, U, is increased by the absolute value of the bias according to Formula below.

$$X_{ucorr} = x \pm [U_{M1} + |b|]$$

When method M1 is used, it can also be appropriate to include additional uncertainty contributions within the RSS term relating to the value of b employed. This will particularly be the case when - the measured hardness is significantly different from the hardness levels of the blocks used during the machine's calibration,

- the machine's bias value varies significantly throughout its calibrated range,
- the material being measured is different from the material of the hardness reference blocks used during the machine's calibration,
- the day-to-day performance (reproducibility) of the hardness testing machine varies significantly.

The calculations of these additional contributions to the measurement uncertainty are not discussed here. In all circumstances, a robust method for estimating the uncertainty associated with b is required.

b. Procedure without bias (method M2)

As an alternative to method M1, method M2 can be used in some circumstances. Method M2 is only valid for hardness testing machines that have passed an indirect verification in accordance with ISO 6507-2 using the value |*b*| +U_{HTM}, rather than only the bias value, *b*, when determining compliance with the maximum permissible deviation of the bias (ISO 6507-2). In method M2, the maximum permissible bias, b_E, (the positive amount by which the machine's reading is allowed to differ from the reference block's value), as specified in ISO 6507-2:2017. There is no correction of the hardness values with respect to the bias limit. The procedure for the determination of *U* is explained in Table 17.

The combined expanded measurement uncertainty for a single future hardness measurement is calculated according to formula below.

$$U_{M2} = k \cdot \sqrt{u_H^2 + 2 \cdot u_{ms}^2 + u_E^2}$$

where:

u_H - contribution to the measurement uncertainty due to the lack of measurement repeatability of the hardness testing machine;

u_{ms} - contribution to the measurement uncertainty due to the resolution of the hardness testing machine. Both the resolution of the length measurement indicating instrument and the optical resolution of the measuring microscope shall be considered. In most cases, the overall resolution of the measurement system should be included twice in the calculation of u_H due to resolving the positions of both ends of the long diagonal independently;

u_E - contribution to the measurement uncertainty due to the maximum permissible deviation of the bias, $u_E = b_E / \sqrt{3}$ (rectangular distribution), where b_E is the maximum permissible deviation of the bias as specified in ISO 6507-2, and the result of the measurement is calculated according to formula below.

$$X = x \pm U_{M2}$$

3.2.2. References Documents

The application of these uncertainty measurements requires the use of the references norms. In cases of dated references, the latest issue of document/norm applies.

EN ISO / IEC 17025	General Requirements for the Competence of Testing and Calibration Laboratories
EN ISO / TR 14253-1	Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment *Part 1: Decision rules for verifying conformity or nonconformity with specifications*
EN ISO / TR 14253-2	Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment *Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification*
EN ISO / TR 14253-3	Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment *Part 3: Guidelines for achieving agreements on measurement uncertainty statements*
EN ISO / TR 14253-4	Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment *Part 4: Background on functionality limits and specification limited in decision rules*
EN ISO / TR 14253-5	Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment *Part 5: Uncertainty in verification testing of indicating measuring instruments*
EN ISO / TR 14253-6	Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment *Part 6: Generalized decision rules for the acceptance and rejection of instruments and workpieces*
EN ISO / IEC 98-3 / Suppl . 1	Uncertainty of measurement *Part 3: Guides to the expression of uncertainty in measurement (GUM:1995)* *Supplement 1: Propagation of distributions using a Monte Carlo method*
PD IEC GUIDE 115:2021	Application of uncertainty of measurement to conformity assessment activities in the electrotechnical sector
SMT4-CT97-2165	Manual of Codes of Practice for the Determination of Uncertainties in Mechanical Tests on Metallic Materials The Determination of Uncertainties in Charpy Impact Testing UNCERT COP 06: 2000
EN 10045-1	Metallic materials - Charpy impact test - Part 1: Test method
EN 10045-2	Metallic materials - Charpy impact test - Part 2: Verification of the testing machine
SMT4-CT97-2165	Manual of Codes of Practice for the Determination of Uncertainties in Mechanical Tests on Metallic Materials The Determination of Uncertainties in Fatigue Crack Growth Measurement UNCERT COP 05: 2000
ASTM E647	Standard Method for Measurement of Fatigue Crack Growth Rates
ASTM E740	Structural Components - Residual Strength
SMT4-CT97-2165	Manual of Codes of Practice for the Determination of Uncertainties in Mechanical Tests on Metallic Materials The Estimation of Uncertainties in Hardness Measurements

	UNCERT COP 14: 2000
EN ISO 6506 / 1	Metallic materials - Brinell hardness test - Part 1: Test method
EN ISO 6506 / 2	Metallic materials - Brinell hardness test - Part 2: Verification and calibration of testing machines
EN ISO 6506 / 3	Metallic materials - Brinell hardness test - Part 3: Calibration of reference blocks
EN ISO 6507 / 1	Metallic materials - Vickers hardness test - Part 1: Test method
EN ISO 6507 / 2	Metallic materials - Vickers hardness test - Part 2: Verification and calibration of testing machines
EN ISO 6507 / 3	Metallic materials - Vickers hardness test - Part 3: Calibration of reference blocks
EN ISO 6508 / 1	Metallic materials – Rockwell hardness test - Part 1: Test method
EN ISO 6508 / 2	Metallic materials – Rockwell hardness test - Part 2: Verification and calibration of testing machines and indenters
EN ISO 6508 / 3	Metallic materials – Rockwell hardness test - Part 3: Calibration of reference blocks
ASTM E 10-96	Standard Test Method for Brinell Hardness
ASTM E 18-97a	Standard Test Methods for Rockwell Hardness of Metallic Materials
ASTM A 370-97a	Standard Test Methods and Definitions for Mechanical Testing of Steel Products
IS 14874	General requirements for the competency of testing and calibration laboratories
EN 10002-Part 1	tension testing – method of testing at room temperature
ASTM E8M	Standard test methods for tension testing of metallic materials (metric)
ISO 5725	Accuracy (trueness and precision) of measurement methods and results
ISO/IEC 98-3	Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement
PD IEC GUIDE 115:2021	Application of uncertainty of measurement to conformity assessment activities in the electrotechnical sector
ISO/TS 21748	Guidance for the use of repeatability, reproducibility and trueness estimated in measurement uncertainty estimation
ISO/TC 69	Application of Statistics Methods, SC 6, Measurement Methods and Results
ISO/TS 19036	Microbiology of Food and Animal feeding stuffs – Guidelines for the Estimation of Measurement Uncertainty for Quantitative Determinations

3.2.3. Bibliography

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10. Application of uncertainty of measurement to conformity assessment activities in the electrotechnical sector; PD IEC GUIDE 115:2021;
11. A Guide on Measurement Uncertainty in Chemical & Microbiological Analysis; Technical Guide 2, The SAC Accreditation Program is managed by SPRING Singapore;
12. ISO 14253-1, Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 1: Decision rules for verifying conformity or nonconformity with specifications;
13. ISO 14253-2, Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification;
14. ISO 14253-3, Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 3: Guidelines for achieving agreements on measurement uncertainty statements;
15. ISO 14253-4, Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 4: Background on functional limits and specification limited in decision rules
16. ISO 14253-5, Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 5: Uncertainty in verification testing of indicating measuring instruments;
17. ISO 14253-6, Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 6: Generalized decision rules for the acceptance and rejection of instruments and workpieces;
18. ISO/IEC GUIDE 98-3/Suppl.1, Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement, Supplement 1: Propagation of distributions using a Monte Carlo method.

3.3. Exercises for the classroom

Based on EN ISO/CEI 17025/2017, all testing laboratories must have and apply a procedure for estimation of uncertainty. Evaluating uncertainty and declaring his value in Analysis report is necessary when the uncertainty is probably to negatively affect the conformity with a specification.

In the next two exercises you will be able to understand more by having two working examples related to the uncertainty measurement in the case of tensile and toughness testing.

3.3.1. Exercise 1 – Calculation of Measurement Uncertainty in Hardness Testing

Values measured on master sample HV10
Measurement 1 188
Measurement 2 188
Measurement 3 190
Measurement 4 193
Measurement 5 192

u_{e2r} – taken from ISO 6507-2 (table 5)
u_{e2r} = 0.0288

X_{CRM} –average hardness value per standard (from the calibration certificate)
X_{CRM} = 192

u_e – incertitudinea standard conform abaterii maxime admise (%)

u_e = 1.97485714 %

u_{CRM} – calibration uncertainty (from calibration certificate)
u_{CRM} = 1 %

u_H – uncertainty of the hardness equipment (from the calibration certificate)
u_H = 0.5 %

x= 190.2

S_x 2.28035085 2.280351
0.25 5.2
4.84
4.84
0.04
7.84
3.24

u_x – uncertainty of easurement marks

t = 1,14 pt n = 5 (n – number of measurements) n= 5
t = 1.14
u_x 1.162576

H= 190.2
d= 0.221 mm
δm= 0.0001 mm

u_{mas} – standard uncertainty

u_{mas} = 0.049689

u_{corr} – revised and extnded uncertainity measurement

K – coverage factor (k=2)
k= 2

u_{corr} = 5.100633 HV

unertainity c= 2.681721 %

3.3.2. Exercise 2 – Calculation of Measurement Uncertainty in Charpy testing

Co-funded by the
Erasmus+ Programme
of the European Union

Breaking energy						
Size	Standard uncertainty	Distribution law	Sensitivity coefficient	Partial uncertainty	Obs.	
a [mm]	0.1	rectangular	1	0.1	electronic comparator	type B
b [mm]	0.1	rectangular	1	0.1	micrometer	
h [mm]	0.1	rectangular	1	0.1	micrometer	
r [mm]	1	rectangular	1	1	microscope	
l [mm]	1	rectangular	1	1	subler	
KV, KU [J]	0.5	rectangular	1	0.5	pendulum hammer	
KV, KU [J] mas	3.38	normal	1	3.38	Measurement	type A
Compound uncertainty				3.70		
Extended Ue uncertainty with a 95% probability				7.4	%	

x	KV
x1	70
x2	78
x3	79
x4	73
x5	76
x6	70
x7	78
x8	72
x9	71
x10	71
x11	77
x12	75
Number of determinations	12
Average	74.16667
Mean squared deviation	3.379977
Um=S/sqrt(n)	0.975715
Um with 95% probability	2.51
Um with 95% probability [%]	**3.38**

x	Cr	EL	raport 40 RAAN / 2009
x1	28	6.86	
x2	27	6.54	
x3	27	6.54	
x4	28	6.75	
x5	28	6.6	
x6	27	7.2	
Number of determinations	6	6	
Average	27.5	6.748333	
Mean squared deviation	0.547723	0.255062	
Um=S/sqrt(n)	0.223607	0.104129	
Um with 95% probability	0.57	0.27	
Um with 95% probability [%]	**2.07**	**4.00**	