

Mechanical Testing of Welds

PART OF THE CWB CERTIFICATE PROGRAMS



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MODULE 12

**MECHANICAL TESTING
OF WELDS**

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Mechanical Testing of Welds

MODULE 12

MECHANICAL TESTING OF WELDS

Introduction

This module describes the various mechanical (destructive) tests that are carried out on welds. Mechanical testing is done for a number of reasons, including certification of welding consumables, and the qualification of welders and welding procedures. The following topics will be covered:

Objectives

- Stress and strain
- The tensile test
- Requirements of various codes for tensile tests
- Bend tests and code requirements
- Nick-break and fillet weld break tests
- Hardness tests
- Impact tests
- Fracture mechanics tests
- Proof tests and fatigue tests

The results of a mechanical test will depend on the way in which it is carried out, and standardized methods should be used to produce meaningful data. When a test is being conducted, reference should always be made to the standard so that the proper procedure is used.

Except in rare cases, where a small sample can be cut from a welded joint for testing, mechanical tests must be performed on separate test plates or samples. In most cases, preparation of the test pieces is also standardized. In some cases, production test plates are actually welded to the ends of the real joints, thus providing the effect of a continuous plate from workpiece to test plate. This has the advantage that the weld is continuous, with no break in the actual welding operation, and the test sample is truly representative of the real weld.

STRESS AND STRAIN

When a metal is subjected to an external force (a load), this will be resisted by internal forces within the metal. The intensity of these forces through a given plane is known as a *stress*. In the simplest example, consider a round rod subject to a load of 1 000 N (newtons) as in Fig. 1. The stress (σ) in the rod is given by the *load divided by the cross-sectional area of the rod*. For example, if the diameter (d) of the bar is 10 mm, then the cross-sectional area is:

$$\pi\left(\frac{d}{2}\right)^2 = \frac{\pi(10)^2}{4} = 78.54 \text{ mm}^2$$

The stress in the rod of Section A-A is therefore:

$$\begin{aligned}\sigma &= \frac{\text{load}}{\text{area}} = \frac{1\,000}{78.54} = \frac{\text{N (newtons)}}{\text{mm}^2} \\ &= 12.73 \text{ N/mm}^2\end{aligned}$$

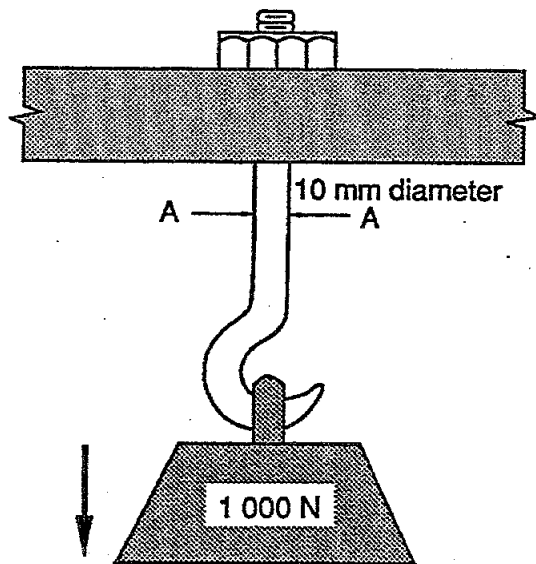


Figure 1. Rod subject to load.

In this example, the stress is uniform across a section of the rod but in many cases it is not. If the stress is not uniform, then it cannot be calculated simply from the *load divided by the total cross-sectional area*. Such is the case in a bending beam, and a more complex calculation is needed to find the stresses at each point in the member.

Units

In the SI (metric system) of units, load (or force) is measured in *newtons* and area is measured in *square meters*. The unit of stress (newtons divided by square meters) is called the *pascal* (Pa). Very often it is more convenient to use the unit of millions of pascals called the *mega-pascal* (MPa). One MPa is the same as one N/mm^2 (newton per square millimeter).

In the Imperial system of units, the load is given in *pounds* (lb) or *thousands of pounds* (kips), and area is measured in *square inches*. Stress is given in the units of *pounds per square inch* (psi) or *thousands of pounds per square inch* (ksi).

To convert ksi to MPa multiply by 6.895

Example: $70 \text{ ksi} = 70 \times 6.895 = 482.65 \text{ MPa}$

Stress states

There are three ways in which a load can act on a cross-sectional area in a body, and these are illustrated by Figs. 1, 2, and 3. They are:

- Tension
- Compression
- Shear

In Fig. 1, the load is trying to stretch the rod, and the force acts perpendicular to the cross-sectional area.

In Fig. 2, the component is being squashed by the load and is under a compressive stress. A column in a building is usually under compression.

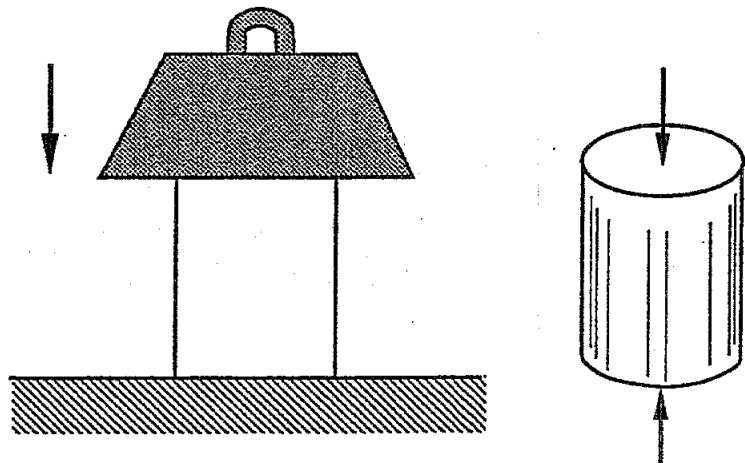


Figure 2. Compression.

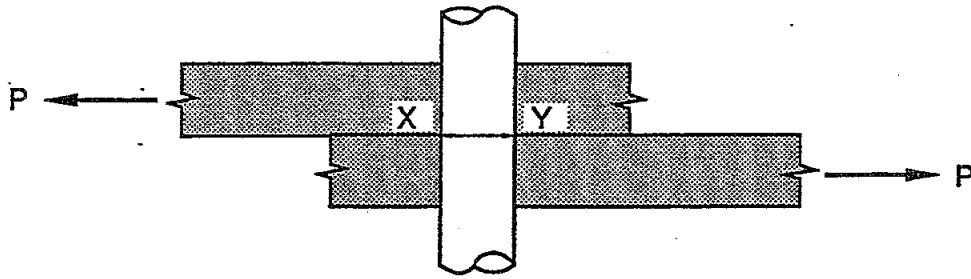


Figure 3. Shear stress in rivet is load "P" divided by a cross-section of "XY."

In Fig. 3, the load is acting parallel to the cross-sectional area of the rivet, and the rivet is under a shear stress. The value of shear stress is still given by *load divided by area*.

It is important to note that, although a component can be thought of as acting in *tension*, *compression* or *shear*, the type of stress depends on the section surface being considered.

In the case of the rod under simple tension (Fig. 1), only the cross-sectional area has a tension stress acting on it. But if another internal surface, such as shown in Fig. 4, is considered, then this may have shear stresses acting on it as well. In fact, it is the shear stresses acting on internal surfaces that allow metals to deform plastically when being loaded in a tension test.

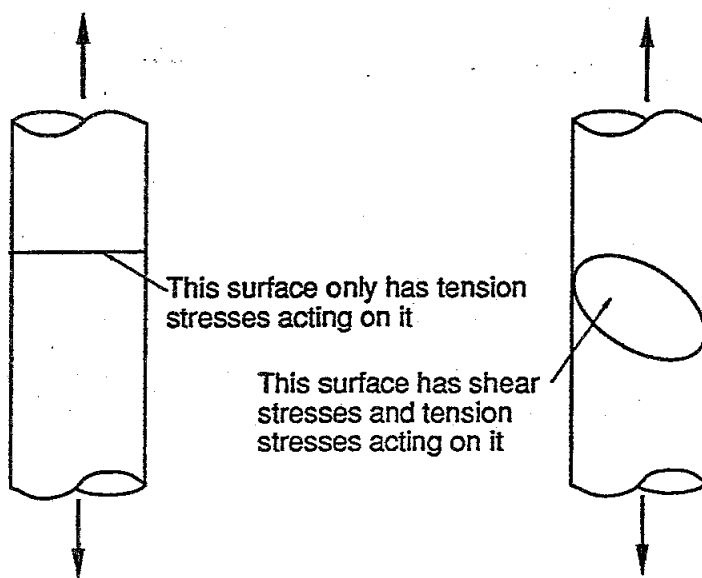


Figure 4. Type of stress depends on surface considered.

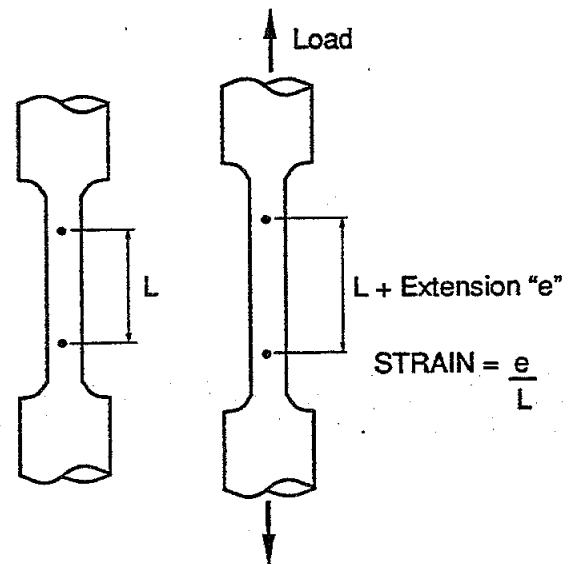
Strain

The strain in a body is a measurement of the change in dimensions. If a bar (Fig. 5) of gauge length "L" is stretched by an amount "e", then the strain "ε" is:

$$\epsilon = \frac{e}{L}$$

i.e., strain is the extension divided by the original length. (This assumes that the extension is small compared with the length, which is true in most practical cases).

Figure 5. Extension of a bar under load.



Strain can be tensile, or compressive, depending on whether the body increases in length, or decreases. There is also a measure for shear strain, but this will not be discussed in this module.

Units of strain

Since strain is a *length divided by a length* it is dimensionless. It may therefore be expressed as a simple number or as a percentage. It is quite common practice, however, to employ the units used for the original measurement of length and express strain in *mm per mm* or *inches per inch*.

For example, if a bar 50 mm long is loaded so that it extends 0.1 mm to 50.1 mm, then the strain is:

$$\text{Strain} = \frac{\text{extension}}{\text{length}} = \frac{0.1}{50} = 0.002 \text{ mm per mm}$$

This may be expressed as 0.002 or 0.2% or 0.002 mm per mm. If the measurements had been made in inches instead, the same answer would have been obtained.

Stress and strain

The application of a stress will result in a strain which may not be in the same direction. In a given direction, it is possible to have a stress without a strain (a condition known as *plane strain*) or a strain without a stress (known as *plane stress*). Fig. 6 shows a simple example.

When the bar is loaded, it stretches and suffers a stress and a strain in the axial direction (along its length). The specimen not only stretches, but also gets a little thinner. It therefore suffers a strain in the transverse direction even though there is no stress in that direction.

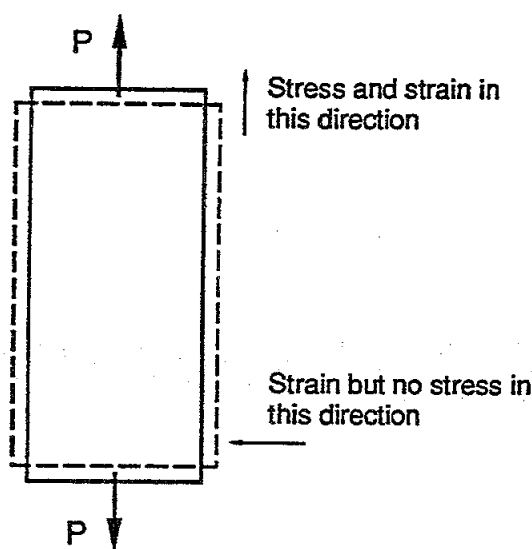


Figure 6. Example of stress and strain.

Elastic deformation

If a bar of metal is subject to a stress, it will deform and exhibit a strain. If the stress is not too high the bar will return to its original dimensions when the stress is removed (see Fig. 7). This is known as *elastic behaviour*. If a plot is made of the stress (load divided by area) against the strain (extension divided by original length) then a straight line will result. The slope of this line, i.e., ratio of the stress to the strain is known as the *Modulus of Elasticity*, "E" (sometimes known as Young's modulus). "E" characterizes the stiffness of a material. The relation between "E", stress and strain is called Hooke's Law where $\sigma = E \epsilon$. The value of "E" depends on the type of material e.g., steel and aluminum have quite different values. The value of "E" for steel is usually taken as 200 000 MPa or, in the Imperial system of units, 29 000 000 psi.

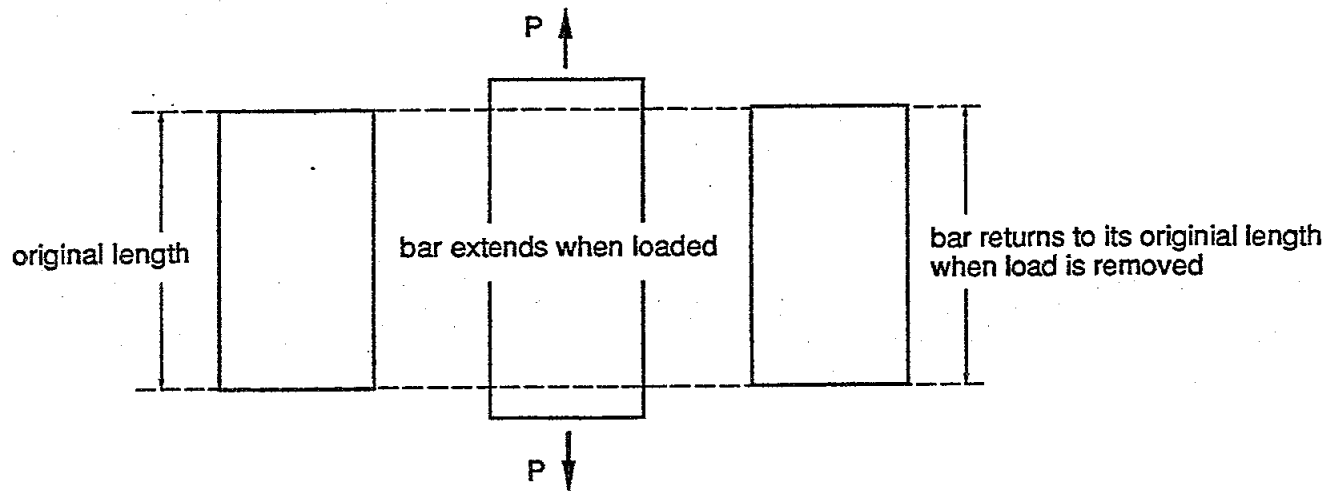


Figure 7. Elastic behaviour of a bar.

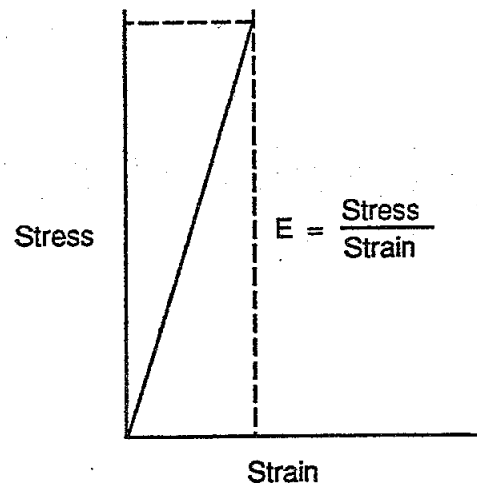


Figure 8. Stress-strain plot for an elastic material and the definition of the modulus of elasticity E .

It will readily be seen that using the previously given formulae for stress and strain that:

$$E = \frac{\sigma}{\epsilon} = \frac{P/A}{e/L} = \frac{PL}{Ae}$$

With this expression several problems can be solved. For example, the total elongation or elastic deformation "e" would be:

$$e = \frac{PL}{AE}$$

(In SI units "e" and "L" are in meters; "A" in square meters, "P" in newtons)

(In Imperial units, "e" and "L" are in inches; "A" in square inches; "P" in pounds and "E" in psi)

Plastic deformation

Deformation is very often a determining factor in design and it should be noted that "E" does not change with an increase in the strength of the steel and neither, therefore, does "e", the sag or deformation for a given "P", "L", and "A". Hence if the extension or deformation of a part made of low strength steel is not acceptable then no benefit will be gained by using a higher strength steel.

If a sufficiently high stress is applied to a bar, it will not return to its original length when the stress is removed (see Fig. 9). In this case where the bar has undergone plastic deformation, the residual strain left when the stress is removed is known as a permanent set.

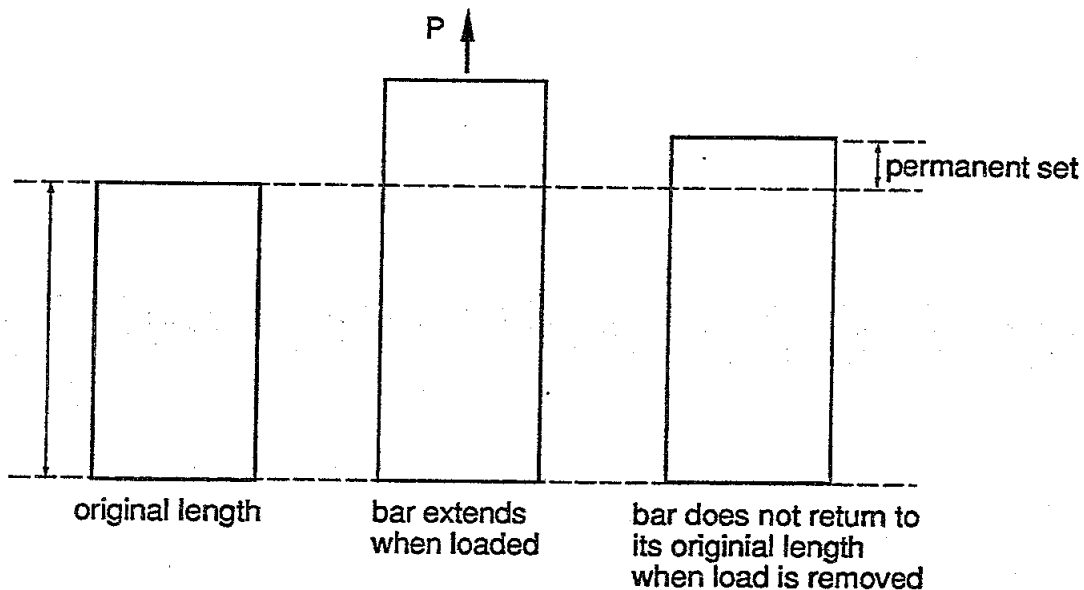


Figure 9. Plastic deformation of a bar.

If a plot of the stress against the strain is made for a bar that undergoes plastic deformation, the result will be as shown in Fig. 10. Initially, deformation is purely elastic and the stress-strain plot is a straight line. At some point, the plot begins to curve over and the specimen stretches with only small increases in load. If the specimen is unloaded, the stress-strain plot will follow a straight line back to zero stress, parallel to the initial elastic line. The permanent set is the final strain when the stress is back to zero.

The stress at which a permanent set is first recorded, when the specimen is unloaded, is known as the elastic limit.

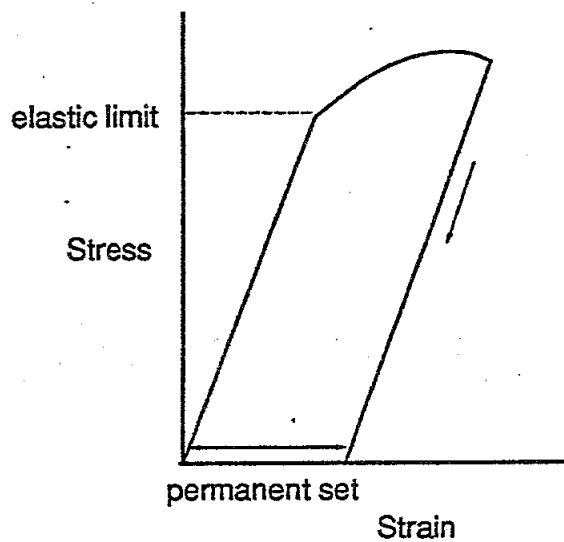


Figure 10. Stress-strain curve for plastic behaviour.

Yield point and yield strength

In some metals, the change from elastic to plastic behaviour is gradual, with the stress-strain plot being a smooth curve.

In many steels, however, there is an abrupt change from elastic to plastic behaviour and the stress-strain curve appears as in Fig. 11. The stress reaches a peak, known as the upper yield point, then drops back a little. The specimen then extends plastically without much change in stress. After the yield strain, the stress begins to rise again in the normal manner.

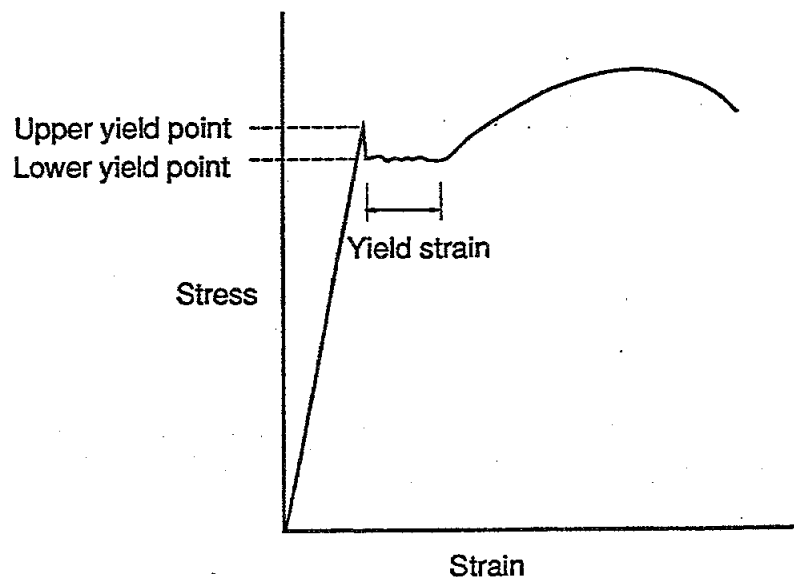


Figure 11. Stress-strain curve for annealed rimmed steel.

The yield behaviour varies widely between steels, some showing large yield drops as in Fig. 11, some showing just a small kink in the curve, and others a smooth change from elastic to plastic behaviour. In metals showing a smooth change, there is no obvious point to take for the yield point. The *yield strength* is, therefore, defined as the stress at which a given permanent set is recorded (usually 0.2%). Fig. 12 illustrates how this is determined. Notice that it must be measured from a stress-strain curve by drawing a line parallel to the elastic line offset by 0.2% strain.

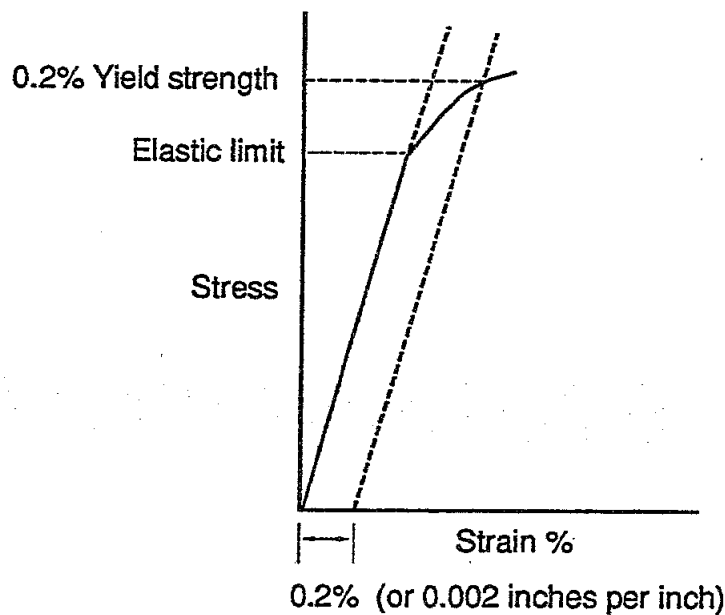


Figure 12. Measuring yield strength by a 0.2% offset method.

It should also be noted that the yield strength of steel is affected by the rate of strain. Relatively high strain rates (i.e., where a specimen is pulled too fast) will increase the yield strength value. Hence most testing specifications place a limit on the rate of strain.

THE TENSILE TEST

If loading of the bar is continued, the specimen will eventually break. The complete stress-strain curve will then appear typically as shown in Fig. 13. The stress rises to a maximum value known as the *ultimate tensile strength* (UTS) then decreases until the specimen finally breaks. If the specimen is observed during the test, it is seen that at some location the specimen begins to become thinner. This is known as necking and the neck begins to form when the UTS is exceeded. Deformation is concentrated in the necked region until it breaks (Fig. 14).

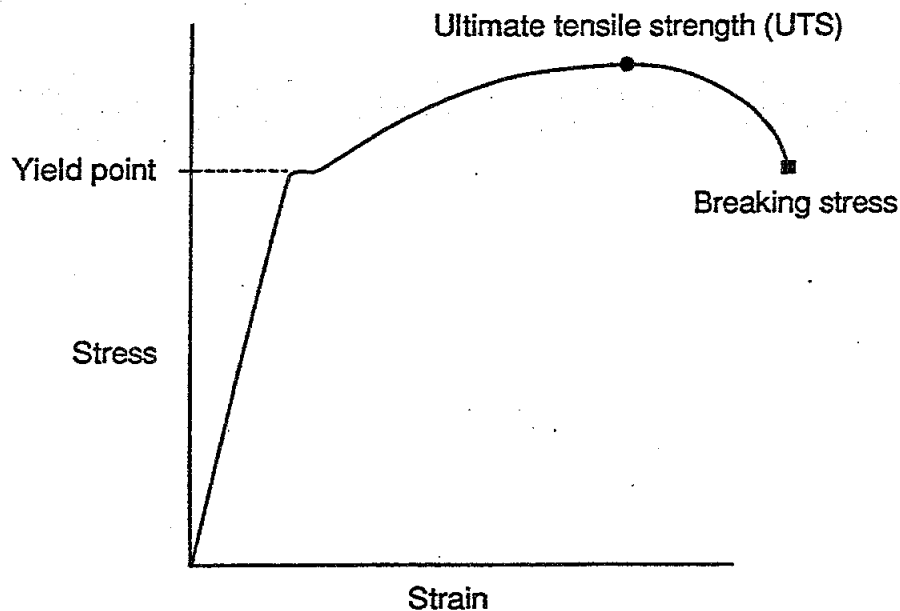


Figure 13. Typical stress-strain curve for steel.

It is important to remember that the stress is the load divided by the *original* cross-sectional area. When the specimen necks, the cross-sectional area at this point decreases. The true stress at the neck will therefore be higher than the stress reported on the stress-strain curve. The same applies to the strain.

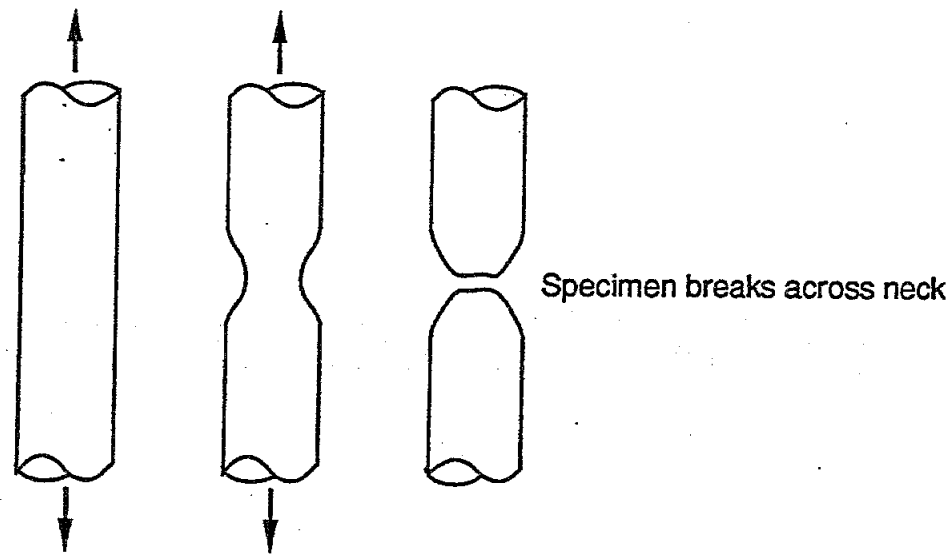


Figure 14. Neck in specimen appears after maximum load is reached.

True stresses and true strains are not commonly used in engineering and therefore all values, such as yield strength, ultimate tensile strength, stress and strain, are based on the original cross-sectional area and the original length of the specimen.

Thus, ultimate tensile strength (UTS) is the maximum load applied divided by the cross-sectional area, and yield strength (YS) is the load applied at the yield point divided by the cross-sectional area. These are expressed mathematically as:

$$UTS = \frac{P_u}{A} \text{ and } YS = \frac{P_y}{A}$$

where P_u = ultimate load on the specimen as indicated by the tensile machine in newtons, (or pounds)

P_y = the yield point load on the specimen as indicated by the tensile machine in newtons, (or pounds)

A = the original cross-sectional area of the specimen in square meters (or square inches).

Elongation

Elongation is a measure of ductility and is determined by measuring the stretch of the metal and expressing this as a percentage of the original length. To determine % elongation, two marks are made on the specimen before testing, and the distance between these two gauge marks is carefully measured. After breaking, the two parts of the specimen are carefully fitted together and the distance between the gauge marks measured again (Figs. 15 and 16).

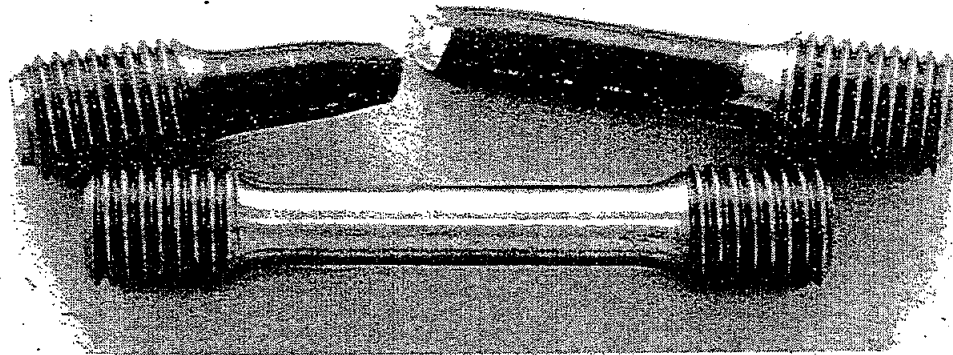


Figure 15. Specimen after tensile test.

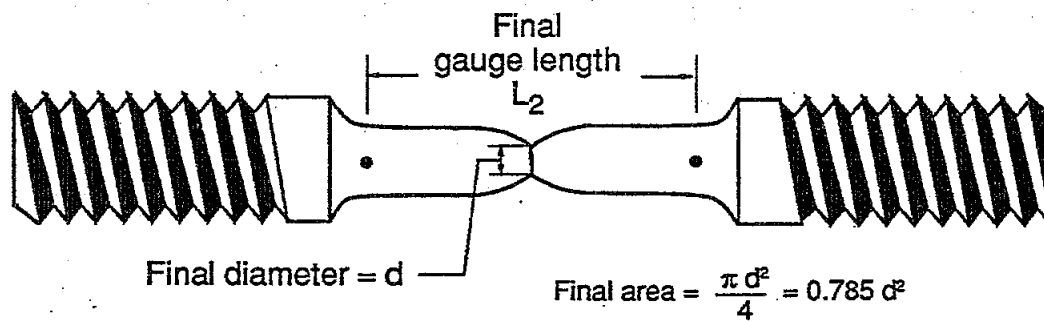


Figure 16. Measurements for elongation, ductility and reduction of area.

Then,

$$\% \text{ Elongation} = \frac{L_2 - L_1}{L_1} \times 100$$

where L_1 = original length
 L_2 = final length

Since the deformation in a tensile specimen is localized, an elongation value is meaningless unless the gauge length is indicated as Fig. 17 illustrates.

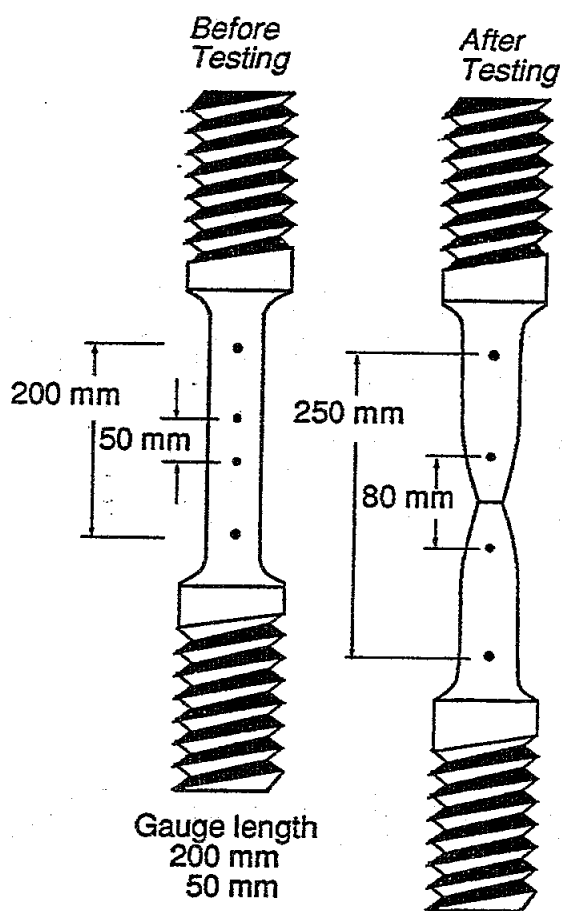


Figure 17. Percentage elongation depends on gauge length.

Elongation
25% at 200 mm gauge length
60% at 50 mm gauge length

Reduction of area

Reduction of area is another measurement related to ductility and measures the decrease in cross-sectional area after necking during the tensile test. After the specimen has been broken, the reduced diameter "d" of the necked-down portion is measured and then the reduced area is calculated as follows:

$$\text{Final area} = \frac{\pi d^2}{4} = 0.785 \times d^2$$

where d = diameter at the neck.

The original cross-sectional area before testing, of course, would be $D^2 \times 0.785$ where "D" is the original diameter.

The formula for the percentage of reduction of area "R" is as follows:

$$R = \frac{A_1 - A_2}{A_1} \times 100$$

where A_1 is the original cross-sectional area of the specimen in square inches, and

A_2 is the cross-sectional area in square inches at the smallest section after breaking.

Equipment for tensile testing

To carry out tensile tests, special machines are needed in order to exert the necessary force. They are generally of two types—*mechanical* and *hydraulic*. In both types there is a fixed and a moving crosshead that applies the force. The specimen is held in special grips connected to the crossheads. In mechanical machines, the force is applied via a screw driven by a motor and gears which allow various crosshead speeds to be achieved.

In the hydraulic machines, force is applied via a hydraulic ram. A wide variation of crosshead speeds can be achieved with the hydraulic system and it is usually possible to slow down almost to a constant load during a test. Fig. 18 shows a typical testing machine.

A variety of methods are used for recording the load. In many of the older hydraulic machines, the load was measured from the hydraulic pressure (either directly or from a separate hydraulic circuit) and displayed on a dial. The dial usually had two pointers, one being free which was pushed by the load recording pointer. If the load dropped (for example, at the yield point) the free pointer would stay at the maximum load. This provided a ready means for recording yield point (upper yield point) and the maximum load.

Most modern machines use load cells to record the load, and then provide an electrical output. The load can be displayed in digital form, or a recorder may be used to plot a graph automatically. Machines with digital displays often have two numbers displayed corresponding to the two pointers on the old machines. Initially, both displays show the same reading, but if the load drops, one display stays at the maximum value. This allows yield point and maximum load to be recorded easily. Some of these machines allow the force to be displayed in either Imperial or SI (metric) units by using electronic conversion. In some cases, the original cross-sectional area may be programmed into the machine so that the value of stress is displayed rather than just the load. This can save time in calculations and may reduce the chance of errors.

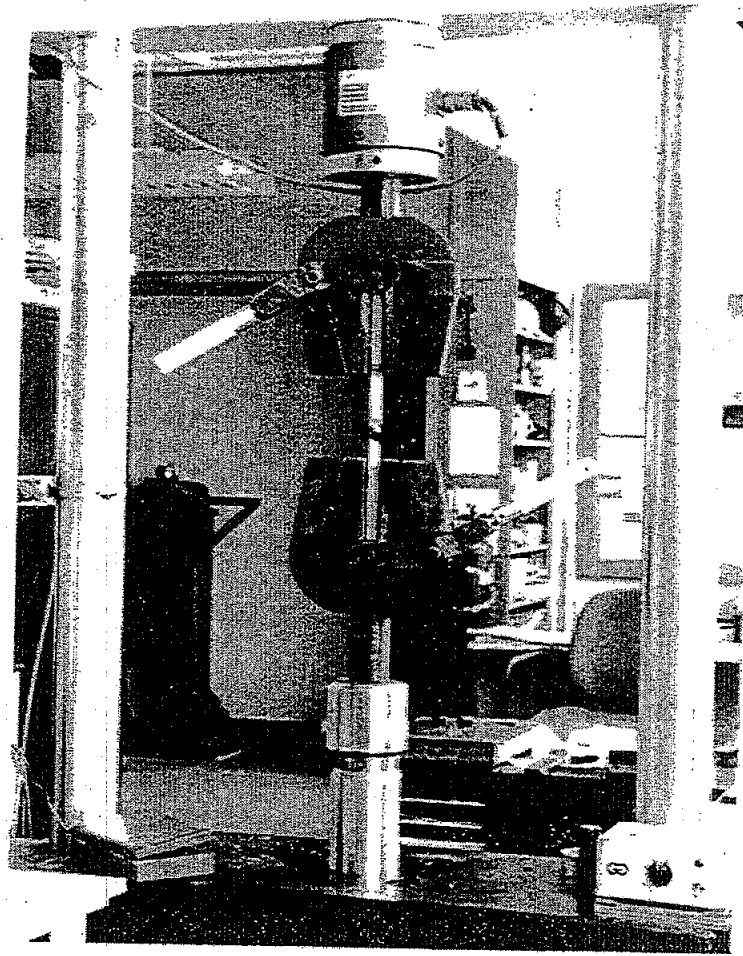


Figure 18. Typical tensile testing machine.

Grips for holding specimens range from simple screw threaded devices to large hydraulically operated clamps. Grips should be inspected frequently for damage or wear to ensure correct operation. Damaged grips can lead to non-axial loading, or slipping of the specimen, which may give misleading results in the test.

If it is desired to measure the strain during a test, an extensometer is placed on the specimen. This is a device that measures the increase in length of the gauge length on the specimen, and the electrical output can be used to drive a recorder. A typical extensometer is shown in Fig. 19. Very often the extensometer must be removed from the specimen after the yield point to prevent damage when the specimen breaks. For many tests conducted on welds, it is not necessary to use an extensometer.

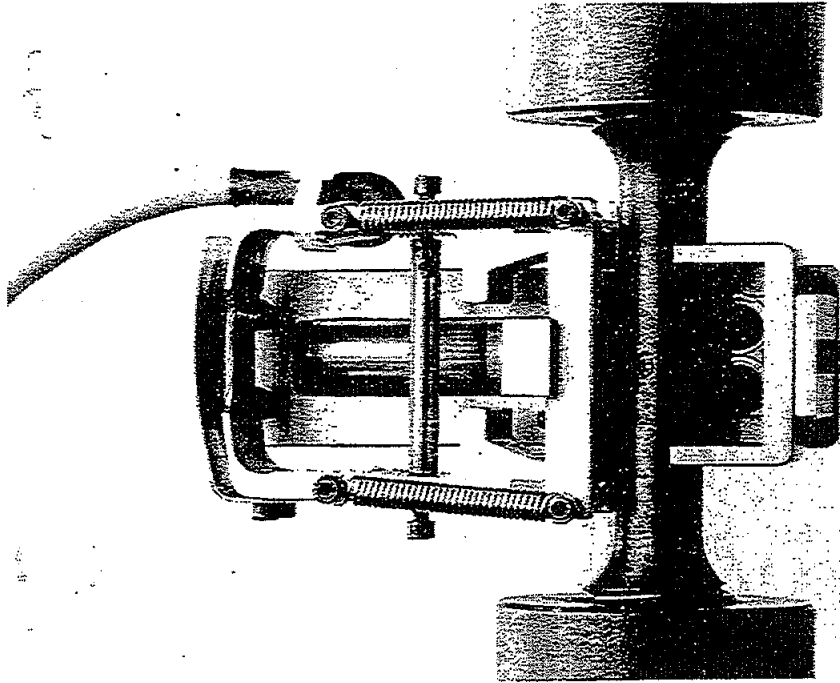


Figure 19. Typical extensometer.

Types of specimens

There are a very large number of standard tensile specimens of various sizes and shapes, only the two most commonly used in the testing of welds will be discussed in this module. These are:

1. *All-weld-metal tensile test specimen.* This is used primarily in the classification of electrodes and is designed to test the tensile properties of a deposit made under standard conditions.
2. *Reduced section tensile test specimen.* This is used in the qualification of welding procedures and is designed to test the strength of the welded joint as a whole, including the weld metal, the heat affected zone and the base metal.

All-weld-metal specimens

Fig. 20 shows the specimen normally used for all-weld-metal tensile tests. The diameter is nominally 0.505 inches in Imperial units, which gives a cross-sectional area of 0.2 square inches, and this simplifies the calculation of the stress. The specimen is often called a "505". The equivalent nominal diameter of the SI specimen is 10 mm. In practice, a tolerance is given on diameter and the actual value would be used to calculate the cross-sectional area.

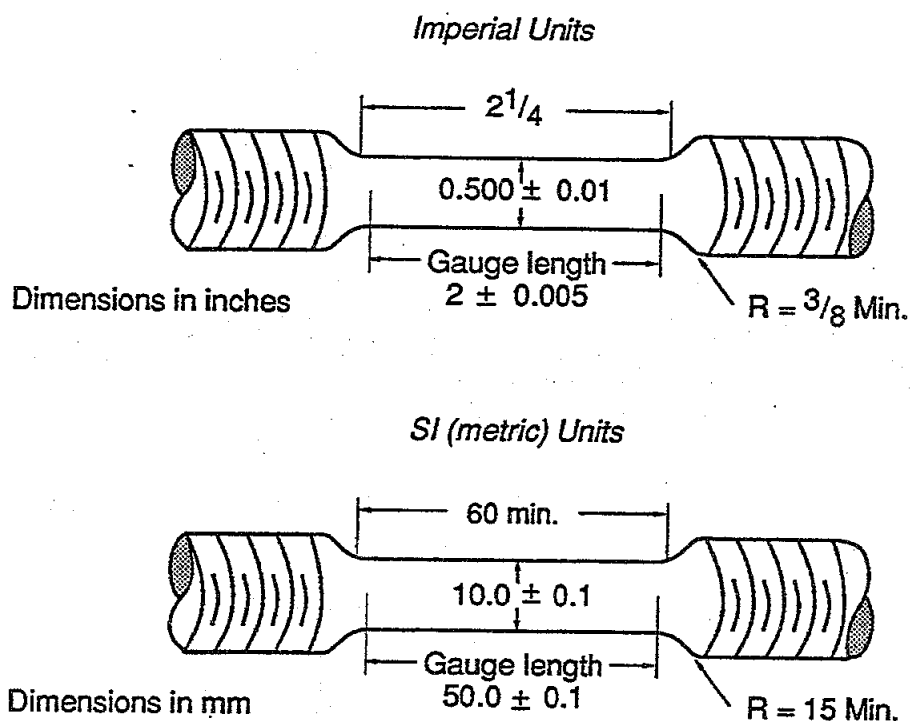


Figure 20. All-weld-metal specimen dimensions. See relevant codes for details.

Specimens with either threaded ends, or with shouldered ends, can be used. The gauge length is marked by two pop marks and this facilitates the measurement of final length when the broken halves are placed back together. The location of the specimen relative to the weld is shown in Fig. 21.

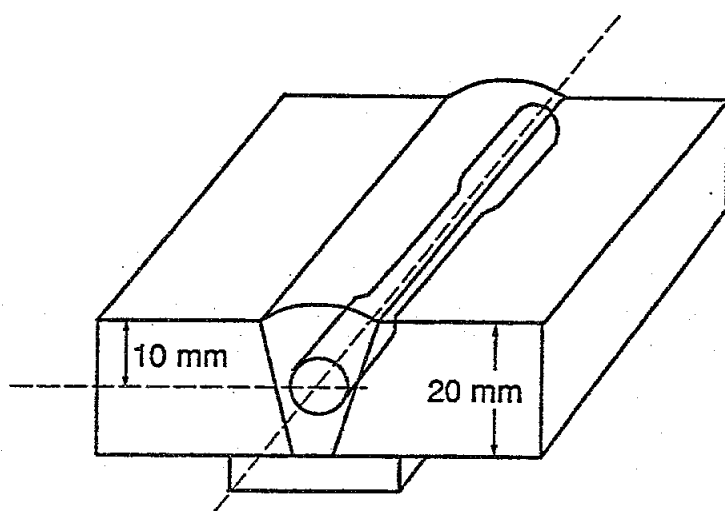


Figure 21. Location of all-weld-metal tensile specimen.

When the specimen shows a distinct yield point, an extensometer need not be used in the test. All required data is obtained from the load and the initial and final dimensions of the specimen.

When the test is used in the classification of welding electrodes, the procedures used for making the weld and for carrying out the test must be carefully followed. The results will not necessarily be the same in a production weld where the welding procedure may be different. Standards, such as the AWS A5 series and the CSA Standard W48 series specify the joint geometry, initial plate temperature and maximum interpass temperature, numbers of passes to use and other details. For mild steel electrode classifications, except basic classifications (low hydrogen type) the machined tensile specimen may be aged at temperatures up to $100^{\circ} \pm 5^{\circ}\text{C}$ for a maximum period of 48 hours prior to testing. The purpose of this is to remove hydrogen which may adversely affect the results of the tensile test.

During the tensile test the crosshead speed of the machine must be controlled. A fast crosshead speed can have the effect of raising the yield point and giving a misleading indication of the weld metal's strength. The CSA and AWS electrode specifications allow any speed up to one half of the specified yield point, but limit it to 3 mm per minute maximum until the yield point is exceeded. For the remainder of the test, the maximum crosshead speed is 25 mm per minute.

Reduction section tensile specimens

The reduced section tensile specimen is used mainly in the qualification of welding procedures. Specimens have a square or rectangular cross-section and are prepared transverse to the weld as shown in Fig. 22. This means that both base material and weld metal are tested.

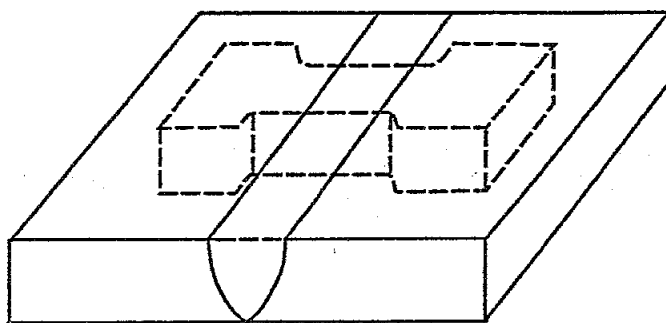


Figure 22. Reduced section tensile specimen transverse to weld.

Unlike the all-weld-metal tensile specimen that only samples some of the weld metal, the reduced section tensile specimen is intended to represent the entire cross-section of the weld. Thus, the specimen thickness is equal to the thickness of the welded plates and only the weld reinforcement is removed. In cases where the plate is so thick that the specimen size would exceed the capacity of the testing machine, several thinner specimens may be taken as indicated in Fig. 23, as long as the entire thickness is represented. An exception to this is the case of electroslog and electrogas welds where only a limited number of test specimens need be taken. CSA W47.1-92 specifies single full thickness specimens for plates up to 38 mm thick and multiple specimens for thicker plates. If multiple specimens are used, the average of all of the results is used.

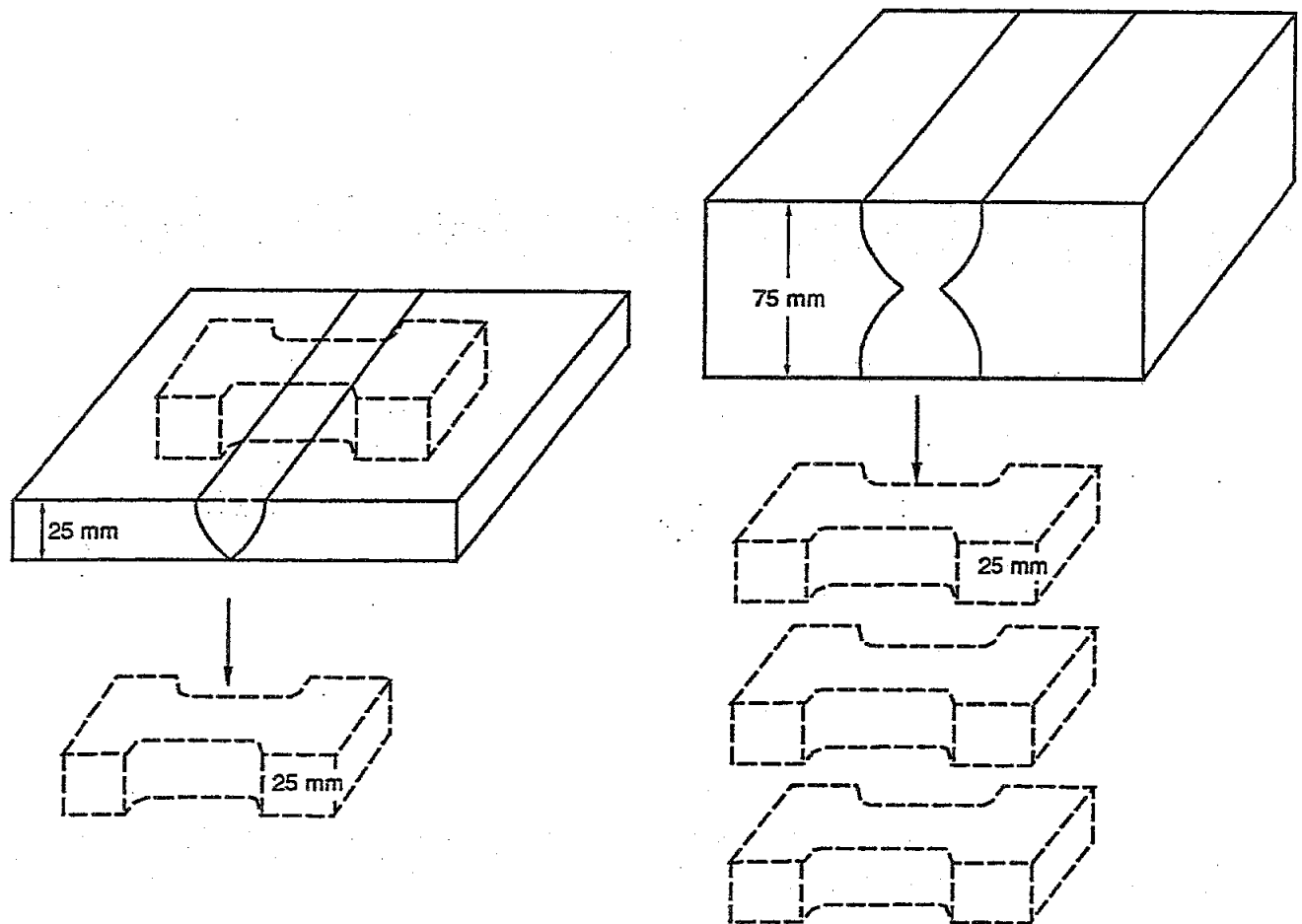
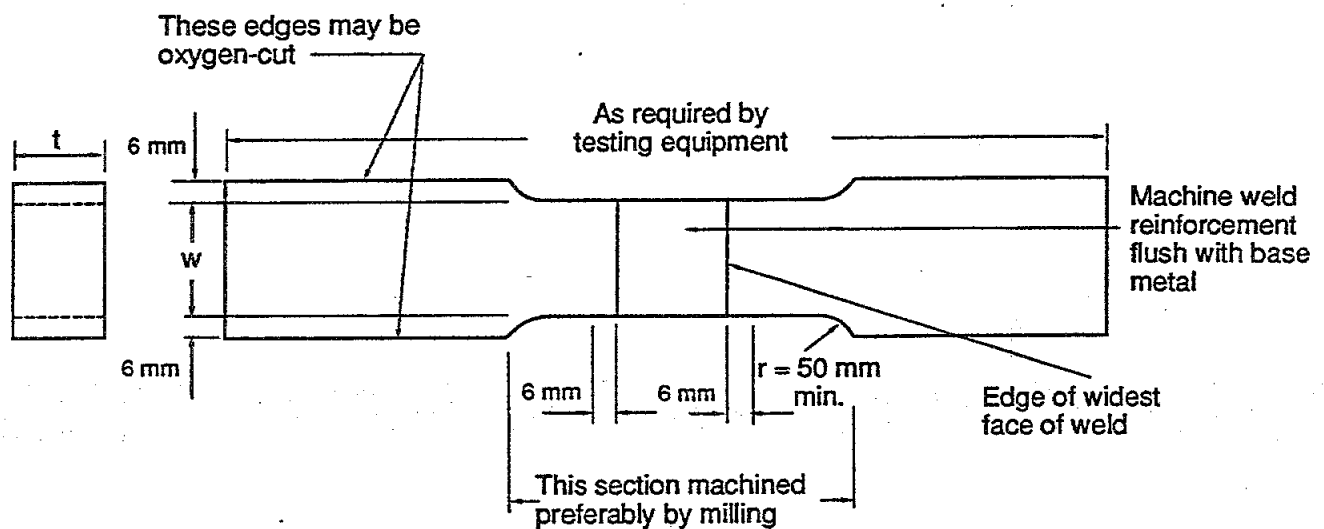


Figure 23. Single and multiple reduced section tensile specimens.

ASME Section IX also allows multiple specimens but, instead of taking the average of the test results, each specimen result is considered individually. Thus, if three specimens are used and one fails to meet the minimum tensile strength, then the procedure test has failed.

The dimensions of a typical reduced section tensile specimen are shown in Fig. 24 and the method of testing in Fig. 25.



- $w = 38 \text{ mm}$ for " t " not exceeding 25 mm
- $w = 25 \text{ mm}$ for " t " greater than 25 mm and not exceeding 38 mm
- $t = \text{plate thickness}$ for plates less than 38 mm thick

For plates thicker than 38 mm specimens shall be cut into the minimum number of approximately equal strips with " t " not exceeding 38 mm thickness.

Figure 24. Dimensions of a typical reduced section tensile specimen.

Before testing, the least width and corresponding thickness of the reduced section are measured to calculate the cross-section area. The ultimate tensile strength is determined by dividing the maximum load reached during the test by the cross-section area. It is not normal to use an extensometer on this test, and the yield point, elongation and reduction in area are not usually determined because the weld metal,

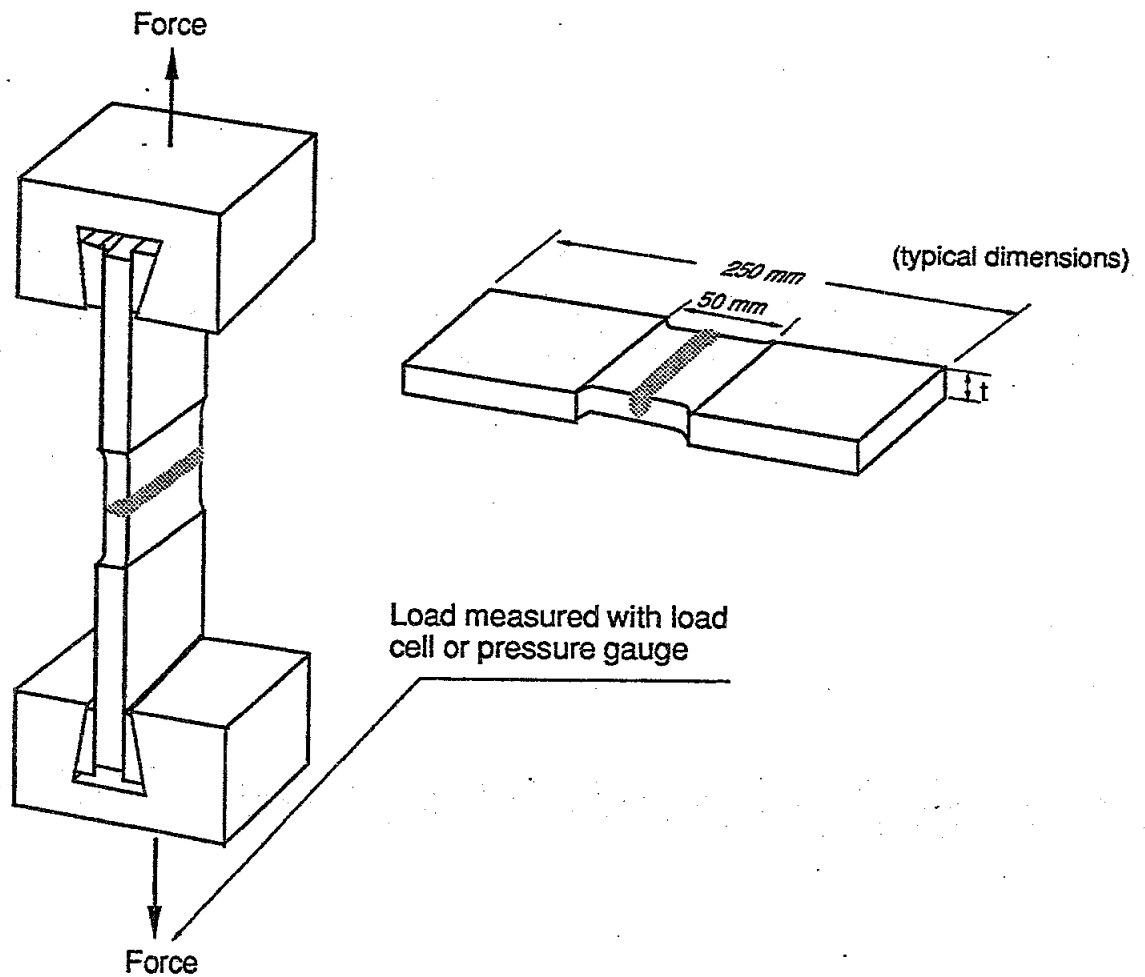


Figure 25. Method of testing reduced section tensile specimens.

heat affected zone, and base metal usually have different yield strengths and ductilities. Therefore, attempting to measure the yield strength and elongation would be meaningless since it cannot be determined where the yielding occurred in the joint. The location of the fracture (i.e., whether in the plate or weld) is recorded, and the fractured surfaces can be examined for evidence of weld defects.

SOUNDNESS TESTS

Bend test

The bend test is a simple but revealing test that has great popularity in welding specifications. It is a very old test, having its origin in the early testing of wrought iron and steel prior to the introduction of modern testing equipment. As with a tensile test, the bend test specimen is such a size and shape that it must be prepared from a test plate, since it would be prohibitively expensive to cut a specimen from the finished structure. The great advantage of the bend test lies in the simplicity of the equipment needed. No expensive test equipment is required, the test specimens can be prepared easily, and the test can be carried out right at the job.

Guided bend test

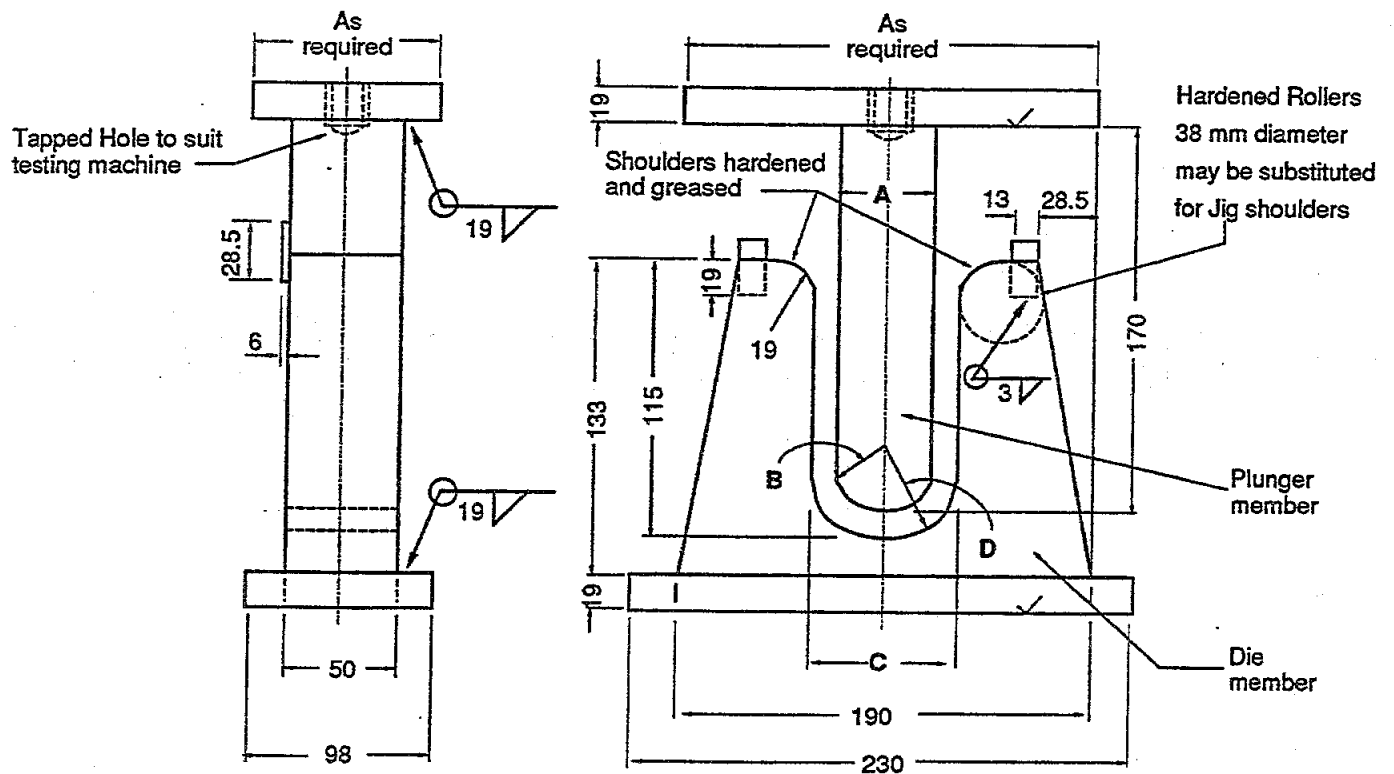
The guided bend test is used in welder and procedure qualification to determine the ability of a welder to make sound welds, or the suitability of a welding procedure.

The test is carried out by preparing specimens and bending them in a special jig, the dimensions of which vary with specimen thickness and material strength. Typical jigs used for bend tests are shown in Figs. 26 and 27. Notice that the strain applied to the specimen depends on the spacing of the rollers and the radius of the plunger. The radius of bending (and hence, applied strain) is lower for higher strength materials.

Care must be exercised in the preparation of the bend samples. To prevent stress raisers and premature failure, the edges should be radiused and all grinding marks should be parallel to the length of the specimen.

After bending, the specimens are examined for flaws or cracks. It is a condition of many codes that the specimens shall be considered to have failed if, on examination of the convex surface after bending, there is a crack or open defect exceeding 3 mm in length measured in any direction. Cracks occurring at the corners of the specimen are disregarded unless there is evidence of a welding defect.

Guided bend tests are of three types—root-bend, face-bend, and side-bend. Root-bends and face-bends are both generally used when the material thickness is 10 mm or less. On material over 10 mm, side-bends are normally chosen due to the difficulty of performing face-and root-



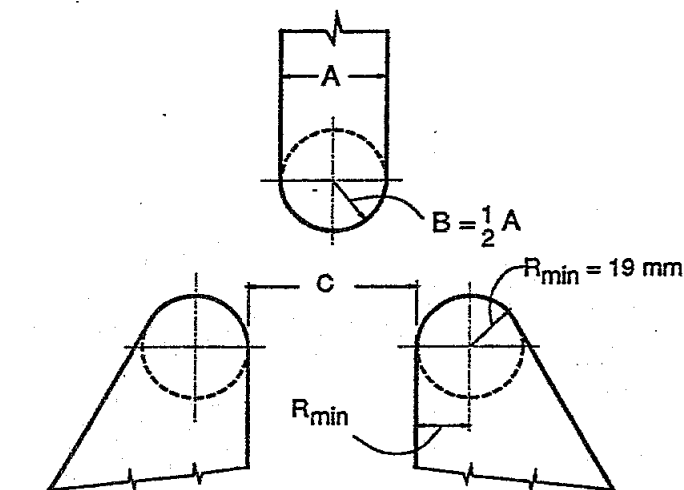
Dimensions in mm

Material Yield Strength (MPa)*	- A - (mm)	- B - (mm)	- C - (mm)	- D - (mm)
345 and under	38	19	66	30
Over 345 to 620	50	25	73	36.5
Over 620	63.5	32	86	43

* Minimum specified

(a) Guided Bend Test Jig

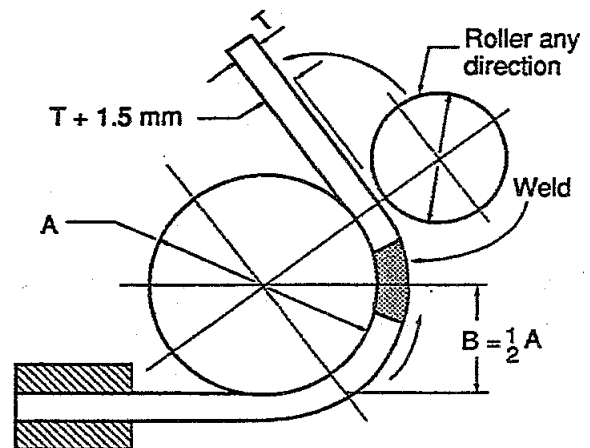
Figure 26. Guided bend test jig. Dimensions shown are for 10 mm specimens.



Material Yield Strength (MPa)*	- A - (mm)	- B - (mm)	- C - (mm)
345 and under	38	19	60
Over 345 to 620	50	25	73
Over 620	63.5	32	86

* Minimum specified

(b) Alternative Roller-Equipped Guided Bend Test Jig for Bottom Ejection of Test Specimen



Material Yield Strength (MPa)*	- A - (mm)	- B - (mm)
345 and under	38	19
Over 345 to 620	50	25
Over 620	63.5	32

* Minimum specified

(c) Alternative Wrap-Around Guided Bend Test Jig

Figure 26 (cont). Guided bend test jig. Dimensions shown are for 10 mm specimens.

bends on material of such thickness. The side-bend specimens are 10 mm thick.

In the face-bend the specimen is bent so that the face of the weld is in tension, and the face of course is on the outside curvature, so that it is under the greatest tensile stress.

In the root-bend, the specimen is bent so that the root of the weld is in tension. This test is very effective in revealing any lack of penetration or lack of fusion at the root of the weld.

In the side-bend, a narrow test specimen is cut across the welded joint. The specimen is then bent sideways so that the tension forces tend to pull the weld metal away from the parent metal over the whole depth of the weld. This test is preferred for double V groove welds since internal defects at the root are more likely to be revealed.

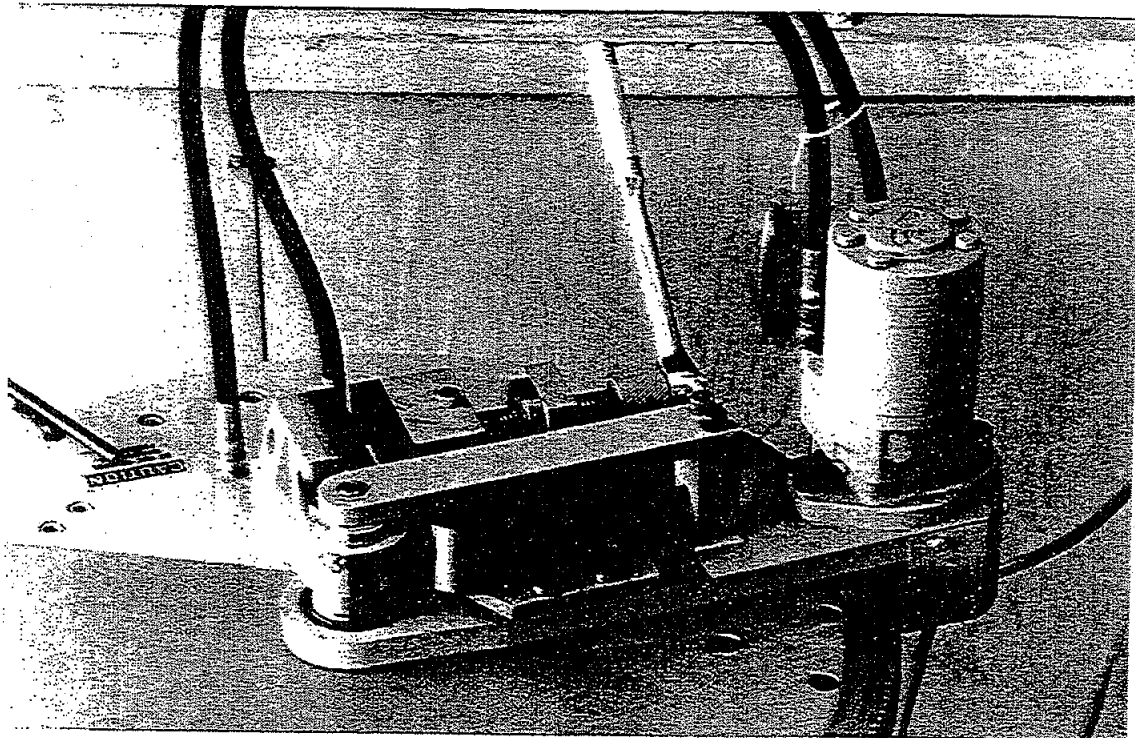


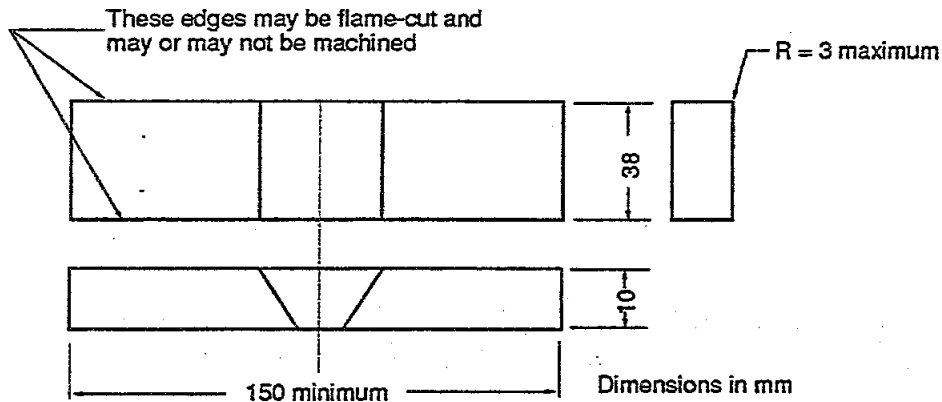
Figure 27. Typical equipment for guided bend testing.

Nick-break test

The location and dimensions of root-, face-, and side-bend tests are illustrated in Fig. 28.

This is an excellent test to reveal internal weld defects. No special equipment is needed; a hacksaw, a hammer, and a vise are the only tools required. Alternatively, the specimen may be broken using a tensile testing machine.

The size of the specimen may vary, but it usually consists of a strip approximately 25 mm wide removed through the weld and parent metal. The specimen is notched on each side at the weld centre and placed in a vise or across supports. It is then struck with a hammer until it fractures through the weld centreline (Figs. 29 and 30).



FACE- AND ROOT-BEND SPECIMENS

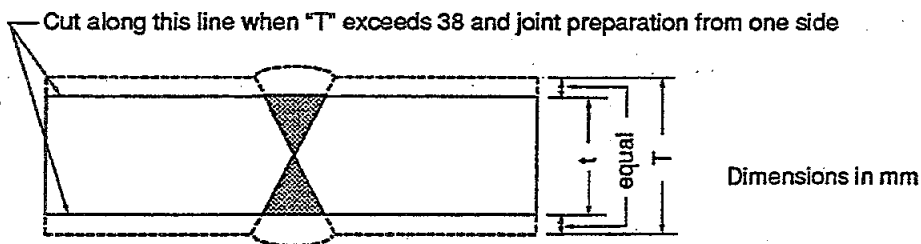
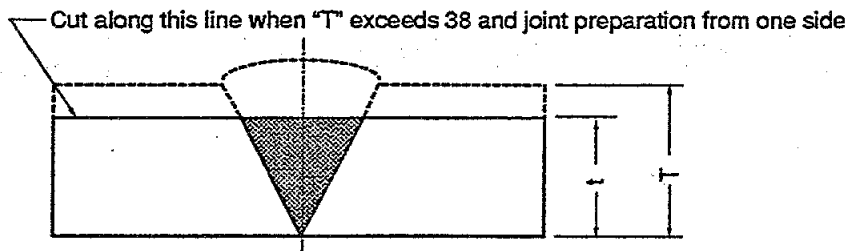
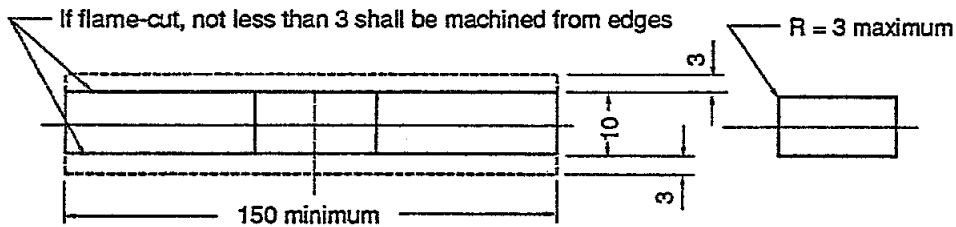


Plate Thickness T – mm	Specimen Dimension t – mm
10 to 38	t
> 38	(see Note)

NOTE

For plates over 38 mm thick cut specimens into minimum number of approximately equal strips not exceeding 38 mm

SIDE-BEND SPECIMENS

Figure 28. Typical location and dimensions of root-, face-, and side-bend tests. Refer to original standards or codes for details and notes.

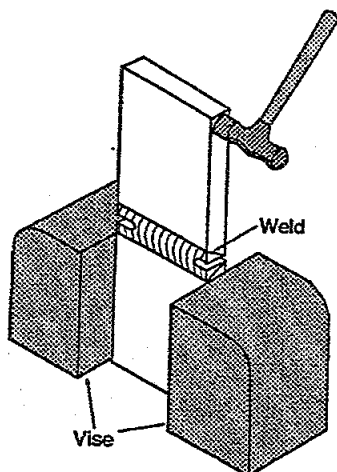


Figure 29. Method for making nick-break test with a hammer and vise.

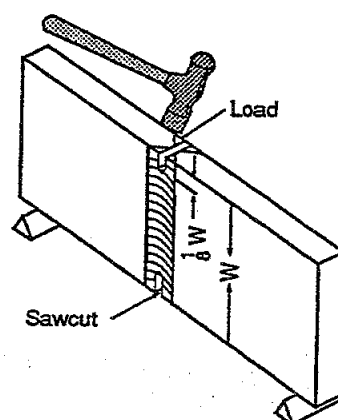


Figure 30. Method for making nick-break test using supports.

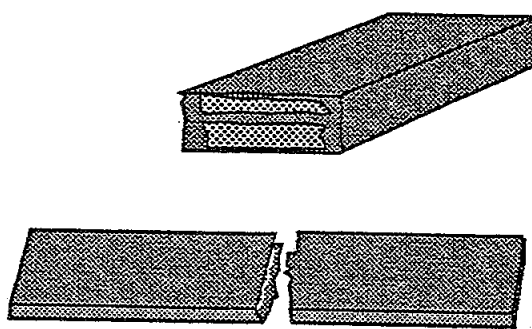


Figure 31. Fractured nick-break test specimens (groove weld mild steel).

The fractured surface (Fig. 31) is examined for defects such as porosity, slag inclusions, lack of penetration and lack of fusion.

Fillet weld break test

The nick-break test will clearly reveal defects if they are present, but it is a spot check only and may not necessarily be indicative of the quality of the entire weld. Difficulty exists in determining acceptability of fractured specimens and, where possible, published acceptability standards should be applied.

The fillet weld break test (Fig. 32) is similar to the groove weld nick-break test and is used to examine the general quality of the weld. The method is to apply a force to the back side of a single welded "T" joint and cause the fillet weld to fracture.

The test is used, for example, in CSA W47 and AWS D1.1 in the qualification of tackers. The test plate is welded in the position in which the tacker is being qualified, then fractured by applying a force. The fractured specimen is examined for porosity, penetration, and other criteria which would determine whether the test has been passed.

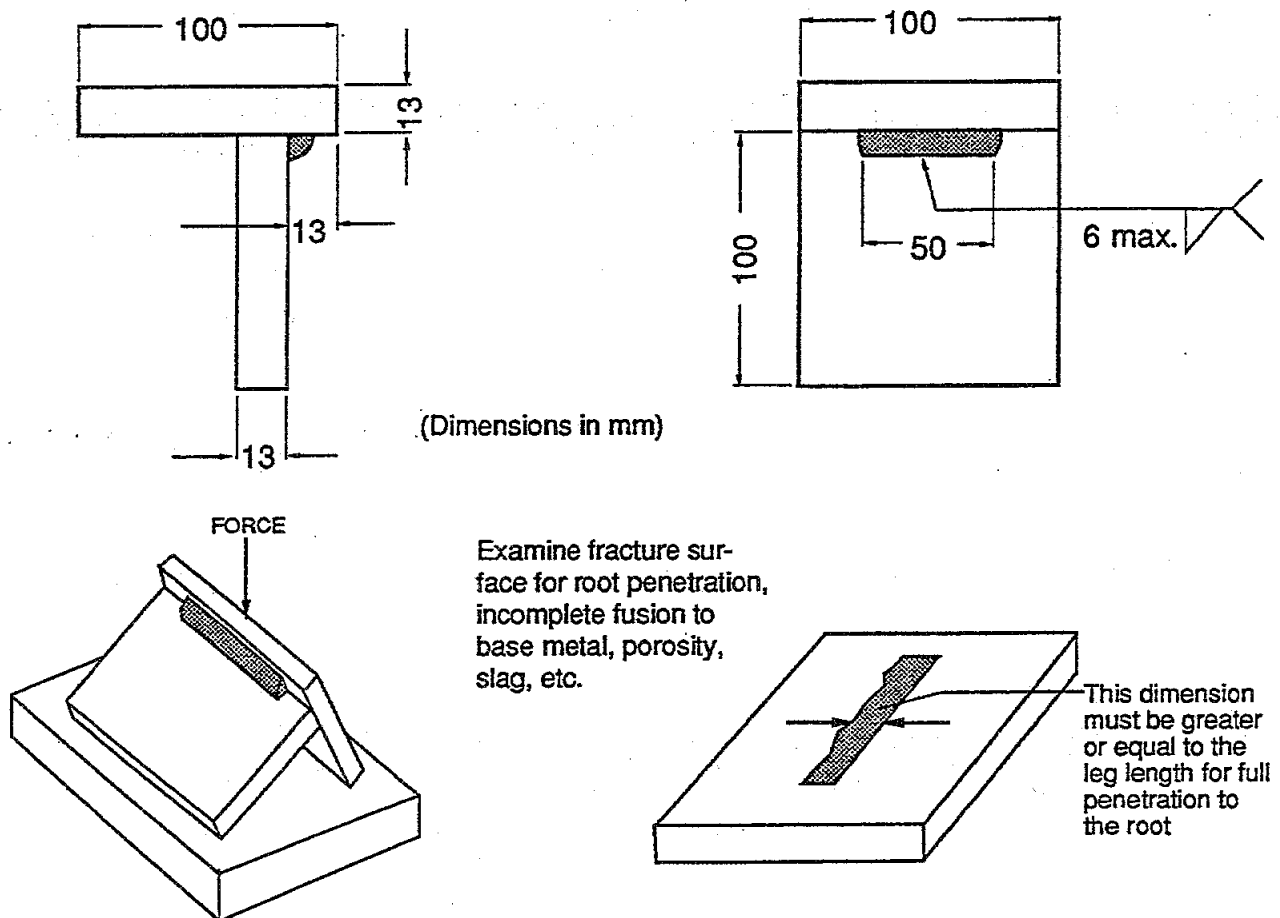


Figure 32. Typical fillet weld break specimen used in the qualification of tackers.

HARDNESS TESTING

Hardness testing is one of the more common methods of testing metals. It is easy and economical and since there is a fairly definite relationship between hardness and some of the mechanical properties of steel, it is informative. The tensile strength of steel will vary in close relation to its hardness. High hardness means high strength and low hardness, low strength. Usually, a high hardness also indicates low ductility.

In regards to welding, hardness is important as it influences, for example, the susceptibility to hydrogen cracking and stress corrosion cracking in wet sulphide service. In the latter case, weld zone hardness is often specified not to exceed 225 BHN. Figs. 33 and 34 illustrate typical testing machines. Small portable units are also available by which quick and relatively accurate check test can be made (Fig. 35).

Generally speaking, hardness testing is an indentation test whereby a penetrator of a given material, shape, and size is forced into the surface of the material being tested by a given load. The degree of hardness is indicated by the depth penetrated or by the area of resulting impression. The Brinell, Vickers, and Rockwell hardness testers operate on this principle.

Recent developments in hardness testing use the principle of measuring the ratio of impact and rebound velocity of a tungsten carbide hammer directed at a test surface. Harder materials produce higher rebound velocities. Velocities are measured electronically and converted to hardness values. As shown in Fig. 36 equipment of this type is compact, lightweight and very portable.

The Brinell tester usually consists of a vertically mounted hydraulic cylinder which is used to force a ball into the surface of the metal to be tested. For steel, the ball is 10 mm (0.394 in.) in diameter, the force applied is 3 000 kg (6 600 lb) and the force is maintained for 30 seconds. The diameter of the impression is read and the Brinell number can be calculated from this. In practice, calculation is unnecessary because there are tables converting the diameter to the Brinell hardness number. The principle of operation is shown diagrammatically in Fig. 37.

Brinell hardness
tester

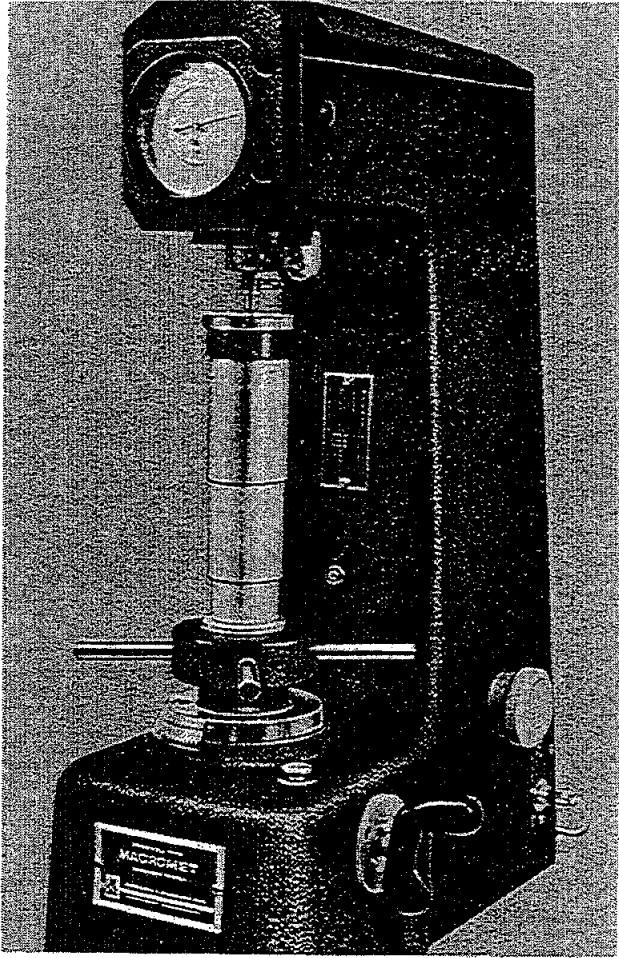


Figure 33. Rockwell hardness tester.



Figure 34. Vickers hardness tester.

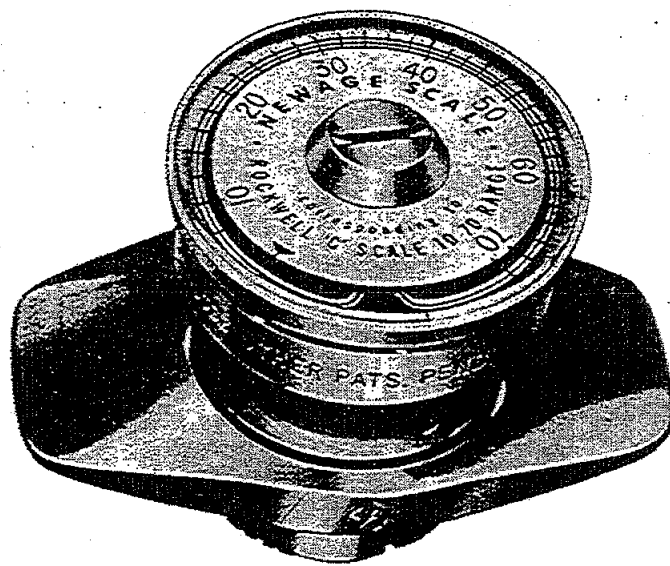


Figure 35. Portable hardness tester.

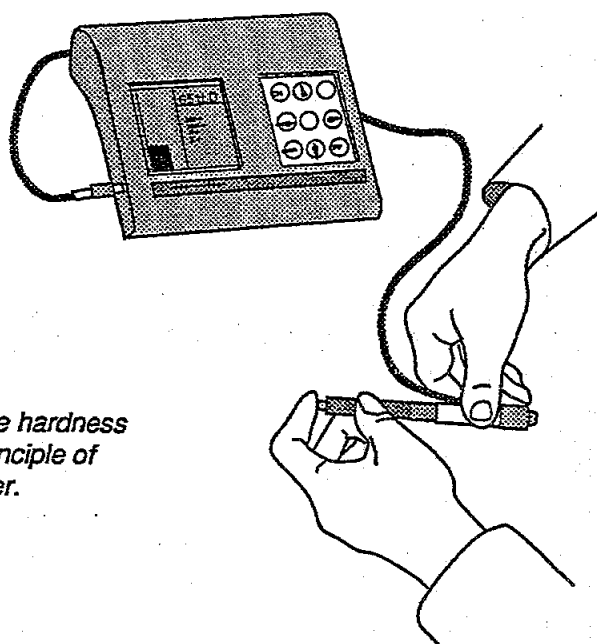


Figure 36. Portable hardness tester based on principle of rebounding hammer.

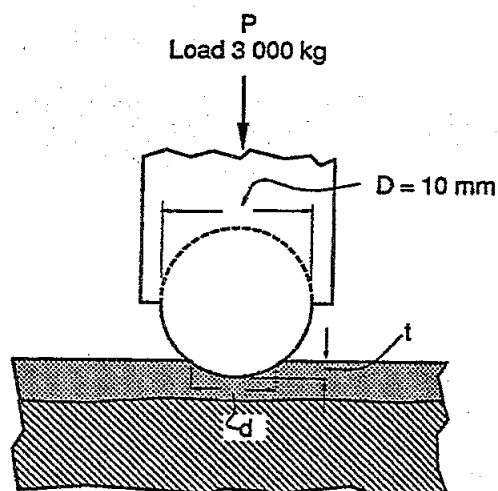


Figure 37. The Brinell hardness test.

$$\text{Hardness} = \frac{\text{Applied load}}{\text{Indentation area}}$$

$$= \frac{P}{\pi D t} = P / \frac{\pi D}{2} (D - \sqrt{D^2 - d^2})$$

Rockwell hardness tester

The Rockwell hardness tester makes use of both a diamond cone (for the hardest materials) and various sizes of steel balls for medium hard materials. Different hardness charts or scales are used for each. The two most commonly used in testing welds are the Rockwell "C" and the Rockwell "B". In the Rockwell "C", a major load of 150 kg is used and the indenter is a conical shaped diamond. In the Rockwell "B", the major load is 100 kg and a 1/16 in. steel ball is used for the indenter.

Note: The scale of the dial is reversed so that a deep impression gives a low reading and a shallow impression a high reading. In this way a high number means a hard material. The "set" position is at 30 on the "B" scale which is used with the ball penetrator.

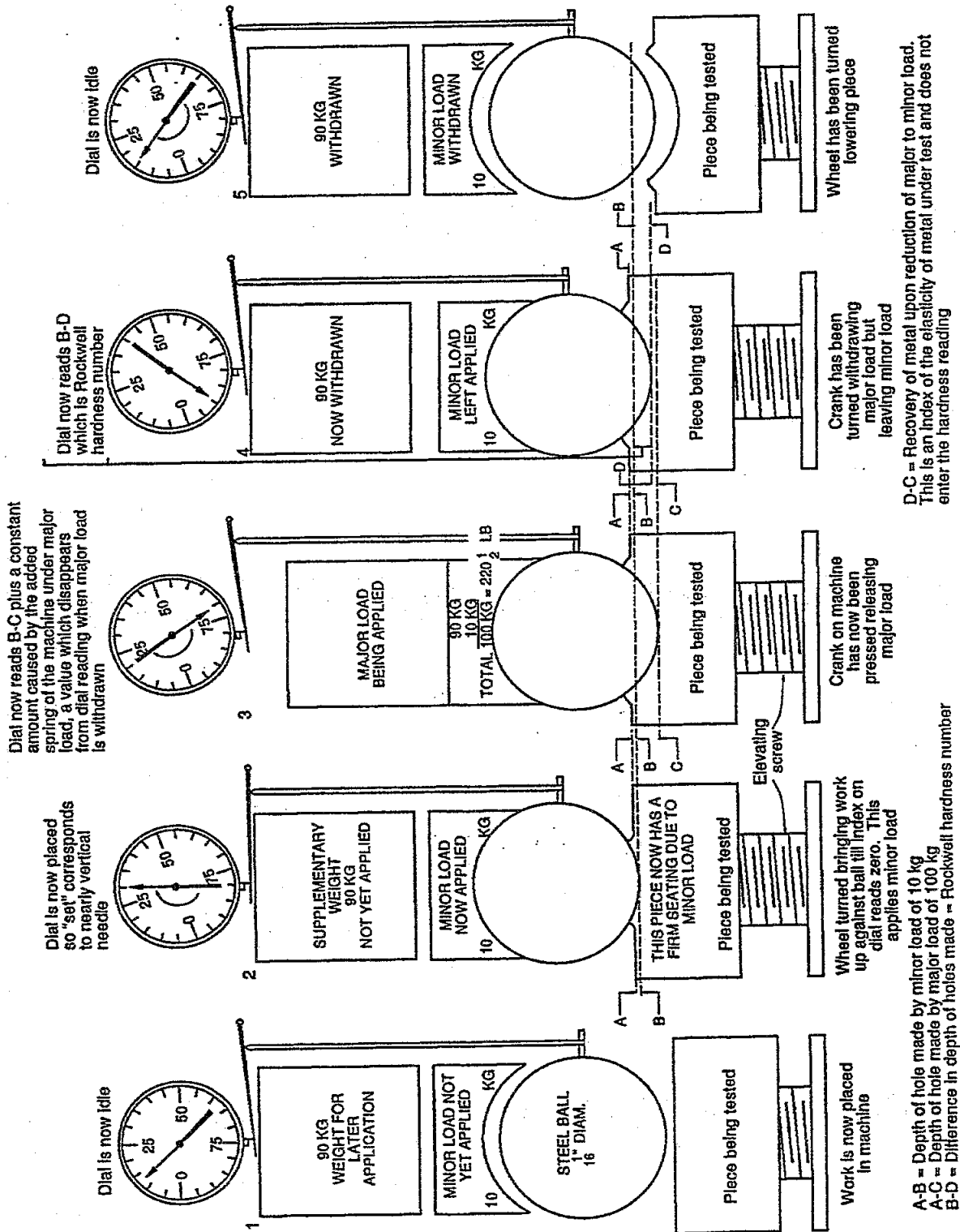


Figure 38. Steps in carrying out a Rockwell hardness test.

Vickers hardness tester

A Rockwell test is made by elevating a specimen against the indenter until a minor load is applied. For "B" and "C" scales this is 10 kg. When this load is applied, the dial indicator is adjusted to a "set" position. The major load is then applied and the rate and time of application are governed by the machine. On completion of the application, the major load is removed and the hardness number is read directly from the dial indicator (see Fig. 38).

The great advantage of this test method is its rapidity. There is no need to measure an indentation. The great range of scales makes it very useful for a great range of hardnesses and for varying thicknesses of material.

The Vickers hardness test originated in England where it is still very popular. It is widely used for testing welds because the size of the indentation is small and it is relatively easy to locate specific regions of the weld for testing. It has the advantage that a wide range of loads can be used to cover materials from very soft to very hard, but it has the disadvantage of the Brinell test in that the size of the indentation has to be measured.

The indenter used is a square-based diamond pyramid and the force applied usually ranges from 5 kg to 100 kg. To make the test, the specimen is brought to within 1 mm of the indenter and the loading mechanism is tripped. The load is automatically applied, dwells for a short time and is automatically removed. When viewed through a microscope, the impression in the specimen appears as a dark square. The diagonals of this square are measured to give an "ocular reading" and from this the hardness number can be calculated. Again, there are tables available that make calculation unnecessary. The letters DPH, DPN or Hv are often used to designate this hardness system. These are derived from diamond pyramid hardness or number. The appearance of the indentation in the microscope is illustrated in Fig. 39 which shows how the width is measured through a microscope equipped with movable knife edges.

Comparison of methods

The Brinell, Rockwell and Vickers testers may be used for both hard and soft, ferrous and non-ferrous metals. The three methods are complementary to each other and have different uses and advantages. The Brinell impression, being large, can only be used for obtaining hardness values over a relatively large area such as the face of a weld, base metal and relatively large cross-sections of these. The Rockwell and Vickers tests, however, can be applied to survey the hardness of relatively small areas—sections of welds, heat affected zones, etc.

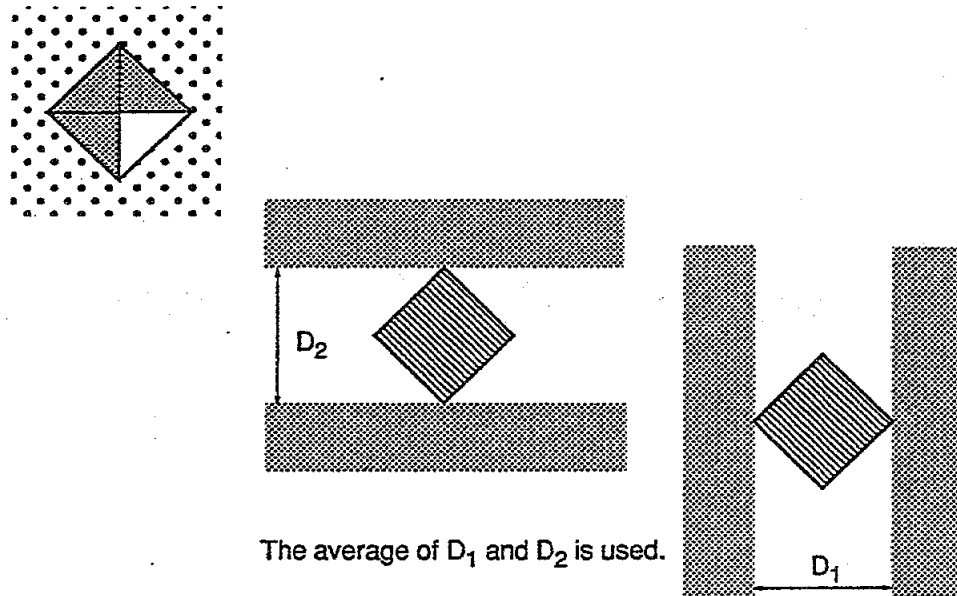


Figure 39. Appearance of indentation in the microscope and method of measuring the width in the Vickers hardness test.

From the information in Table 1 the reader may convert the hardness values obtained by each of the three methods to any other one, and also to the corresponding tensile strength in steel. It should be recognized that to arrive at a tensile strength, the average of a number of hardness values should be taken. The relationship between hardness and tensile strength for other materials is shown in Fig. 40. The relationships are approximate only and should be used only as a guide.

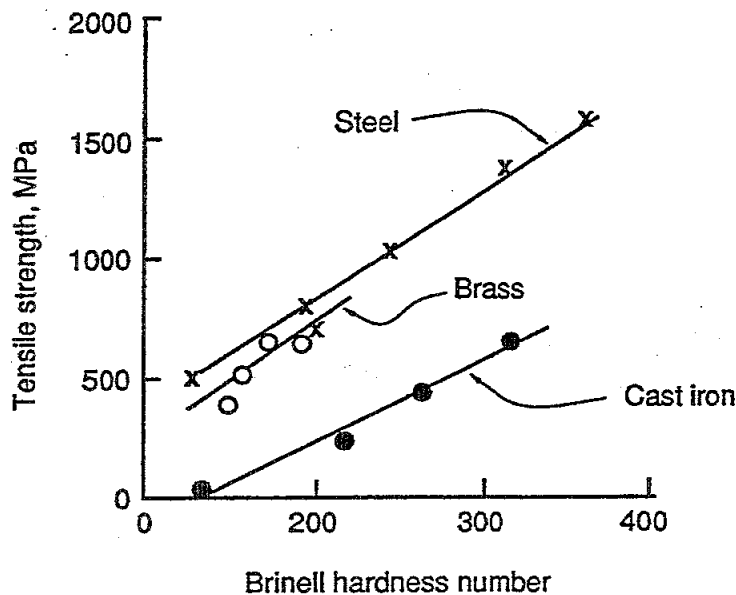


Figure 40. Tensile strength versus Brinell hardness number (BHN) for several materials.

Mechanical Testing of Welds

Table 1. Hardness values of Brinell, Rockwell, and Vickers tests and corresponding tensile strengths of various steels.

Rockwell Hardness		Vickers Hardness	Brinell Hardness		Steel Tensile Strength 1000 psi	Rockwell Hardness		Vickers Hardness	Brinell Hardness		Steel Tensile Strength 1000 psi
C-150 Kg Load, Diamond	B-100 Kg Load, 1/16 Ball	Diamond Pyramid	Tungsten Carbide Ball	Steel Ball		C-150 Kg Load, Diamond	B-100 Kg Load, 1/16 Ball	Diamond Pyramid	Tungsten Carbide Ball	Steel Ball	
67		918	820	.....	.....	20	98.9	240	231	225	107
66		884	796	.....	.....	19	98.1	235	226	220	106
65		852	774	.....	.....	18	97.5	231	222	215	103
64		822	753	.....	.....	17	96.9	227	218	210	102
63		793	732	.....	.....	16	96.2	223	214	206	100
62		765	711	.....	.....	15	95.5	219	210	201	99
61		740	693	.....	.....	14	94.9	215	206	197	97
60		717	675	.....	.....	13	94.1	211	202	193	95
59		694	657	.....	.....	12	93.4	207	199	190	93
58		672	639	.....	.....	11	92.6	203	195	186	91
57		650	621	.....	.....	10	91.8	199	191	183	90
56		630	604	.....	.....	9	91.2	196	187	180	89
55		611	588	.....	.....	8	90.3	192	184	177	88
54		592	571	.....	.....	7	89.7	189	180	174	87
53		573	554	.....	283	6	89	186	177	171	85
52		556	538	.....	273	5	88.3	183	174	168	84
51		539	523	500	264	4	87.5	179	171	165	83
50		523	508	488	256	3	87	177	169	162	82
49		508	494	476	246	2	86	173	165	160	81
48		493	479	464	237	1	85.5	171	163	158	80
47		479	465	453	231	0	84.5	167	159	154	78
46		465	452	442	221	.....	83.2	162	153	150	76
45		452	440	430	215	.....	82	157	148	145	74
44		440	427	419	208	.....	80.5	153	144	140	72
43		428	415	408	201	.....	79	149	140	136	70
42		417	405	398	194	.....	77.5	143	134	131	68
41		406	394	387	188	.....	76	139	130	127	66
40		396	385	377	181	.....	74	135	126	122	64
39		386	375	367	176	.....	72	129	120	117	62
38		376	365	357	170	.....	70	125	116	113	60
37		367	356	347	165	.....	68	120	111	108	58
36		357	346	337	160	.....	66	116	107	104	56
35		348	337	327	155	.....	64	112	104	100	54
34		339	329	318	149	.....	61	108	100	96	52
33		330	319	309	147	.....	58	104	95	92	50
32		321	310	301	142	.....	55	99	91	87	48
31		312	302	294	139	.....	51	95	86	83	46
30		304	293	286	136	.....	47	91	83	79	44
29		296	286	279	132	.....	44	88	80	76	42
28		288	278	272	129	.....	39	84	76	72	40
27		281	271	265	126	.....	35	80	72	68	38
26		274	264	259	123	.....	30	76	67	64	36
25		267	258	245	120	.....	24	72	64	60	34
24		261	252	247	118	.....	20	69	61	57	32
23		255	246	241	115	.....	11	65	57	53	30
22	100.2	250	241	235	112	.....	0	62	54	50	28
21	99.5	245	236	230	110	.....					

1000 psi = 6.895 MPa

500 X BRINELL $\approx$ TENSILE STRENGTH.

Precautions in hardness testing

Correlating the Brinell hardness number and the tensile strength of various steels, it will be found that the tensile strength in psi of a given steel is approximately 500 times its Brinell hardness number. In determining the tensile strength of steels in this rough way, it may be stated that as a rule, the tensile strength will be slightly low for hardness under 200 and above 400 Brinell. Between these two limits, the estimated tensile strength is slightly above the actual strength.

In all hardness tests, many factors affect the accuracy of results. Unfortunately, many people ignore simple precautions and produce inaccurate results. Care must be taken to ensure that the correct load is applied. If the wrong load is used, the result is meaningless. It is essential that there be no friction in the loading system of the machine or a lighter load will result. The machine should be serviced regularly. Impact loading must be avoided. Careless loading can break a diamond indenter and can also cause misshapen impressions which are a source of error.

The condition of the indenter is very important. Ball indenters are very prone to flatten after continued use and this tends to give a low reading. This fault is very prevalent in Brinell testers using a steel ball. For this reason, Brinell is not used at hardness above 500 BHN. Diamond points chip very easily and chipped diamonds give incorrect results that are usually higher than true. The anvil must be kept in good condition, and it must be clean and smooth. Any indentations in the anvil tend to have raised edges and these cause serious errors, usually as low readings. Great care must be taken in measuring the size of an indentation. It does not take much error in reading to give a great variation in results.

The thickness of the specimen is very important. If the specimen is too thin, the indentation effect goes right through and into the anvil. This is obviously incorrect. If the back of the specimen shows any indication of the impression, the test is incorrect and the result should be disregarded. As a rough rule, the specimen thickness should be at least ten times the depth of the impression.

The surface should be flat and must be perpendicular to the axis of the indenter. Otherwise the indenter will tend to slide sideways and give a false reading. The surface has to be smooth enough to allow accurate measurements to be made. Usually filing plus a light polish with emery paper is sufficient for Brinell, but Rockwell and Vickers need polishing with a 320 grit abrasive paper.

Hardness testing in welds

The specimen must be firmly supported with no rocking. The indentation should be far enough from the edges to ensure good support and prevent bulging.

Hardness measurements made in various regions of the weld can be very revealing. For, example, the hardness in the heat affected zone (HAZ) of the parent metal just adjacent to the fusion line may indicate how rapidly the weld has cooled and whether it may be prone to cracking. Selecting a welding procedure that keeps the HAZ hardness below a certain level is a useful way of preventing cracking.

A comparison between the weld metal hardness and the parent material gives a rough guide as to whether the weld metal overmatches the parent. Hardness tests can be useful, quick guides in the identification of an incorrect material. Typical weld metal hardnesses are shown in Table 2.

Table 2. Typical weld metal hardnesses for various electrodes.*

SMAW		
E48018		150-170 HB
Hardfacing electrodes (.4 C, 2.1 Cr)		375-480 HB
FCAW		
E4802T-1		200-225 HB
SAW		
F4802-EM12K		140-180 HB

*Actual hardness will depend on electrode manufacturer, dilution, base metal chemistry, welding procedure, etc.

Information from several regions of the weld may be obtained by conducting a hardness traverse or a complete pattern. Fig. 41 shows results from a typical linear traverse, where several indentations, equally spaced in a line across the weld, are made. The distinct difference between the as-welded and stress relieved results can often be used to check whether stress relieving has been undertaken. A detailed pattern for surveying the hardness of a fillet weld is shown in Fig. 42.

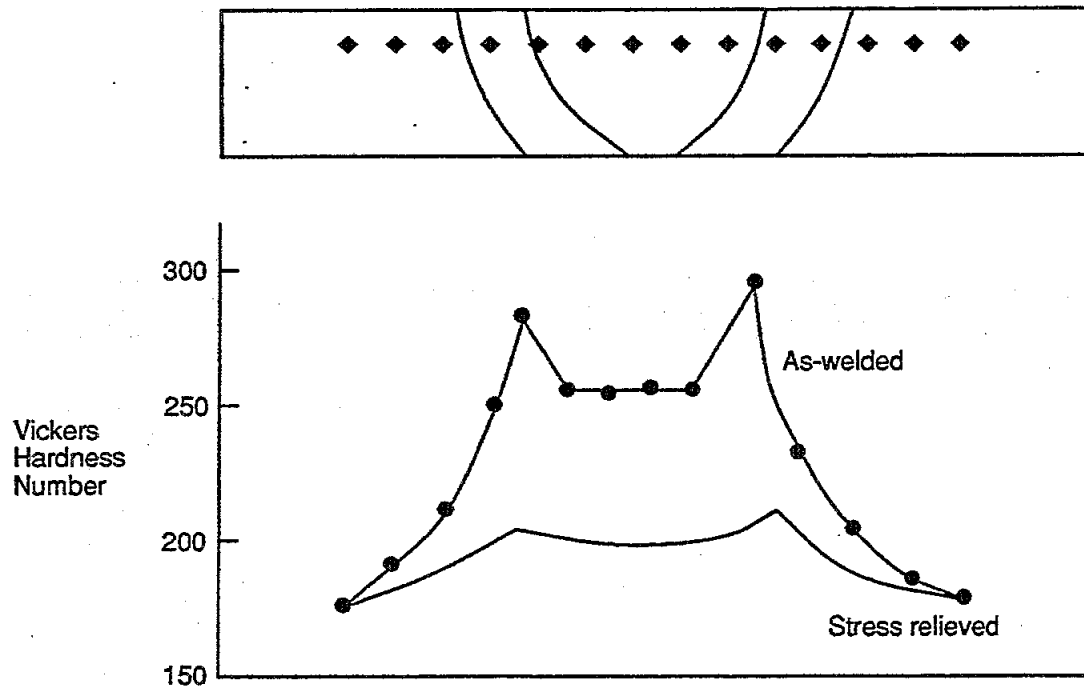


Figure 41. Typical results from a linear hardness traverse across a weld showing both as-welded and stress relieved results.

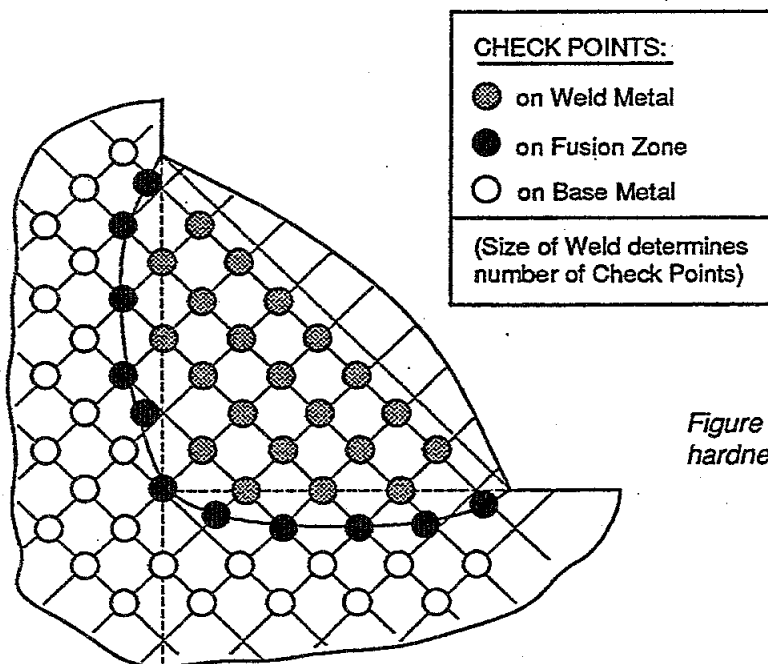


Figure 42. A typical pattern of hardness check points.

TOUGHNESS TESTS

In the section on tensile testing, it was shown how the percentage elongation, or reduction in area, was a measure of the material's ductility. It is possible, however, that a welded structure, made from a material showing good ductility in a tensile test, could still fail in a completely brittle manner. There have been many examples of unexpected brittle fractures in structures such as ships, bridges, and pressure vessels, and they have often occurred when the stresses were well below the yield stress. The reason is that many materials which may show good ductility in a plain tensile test, behave in a completely different manner when notches or cracks are present. They may also behave differently because of impact loading or a low temperature. Steels, in particular, tend to become more brittle when sharp notches are present, when the temperature is low or they are subject to impact loads.

In order to measure the toughness of a material, and to reveal its behaviour in the presence of notches, several tests have been devised. Many of these tests are strictly empirical and are useful for comparing materials, or as quality control checks, but do not necessarily predict the behaviour of a real structure. Other tests (fracture mechanics tests) are more quantitative and in some cases can actually be used to predict a failure stress in a real structure if the size of the notches or cracks is known.

The impact test

The most common toughness test is the *Charpy impact test* in which a notched specimen is broken by a swinging pendulum and the amount of energy required to break the specimen is recorded. The energy can be measured simply by allowing the pendulum to drop from a fixed height and measuring how high it swings up after fracturing the specimen. If the specimen is brittle and absorbs little energy, the pendulum will swing up almost to its original height. If the specimen is tough, the pendulum will only swing up a small distance. The value of energy absorbed is read directly from a dial on the machine and is measured in joules or foot-pounds (ft lb). A typical impact testing machine is shown in Fig. 43.

Charpy impact tests provide comparative data which can be used for qualification or quality control checks on materials. The Charpy value

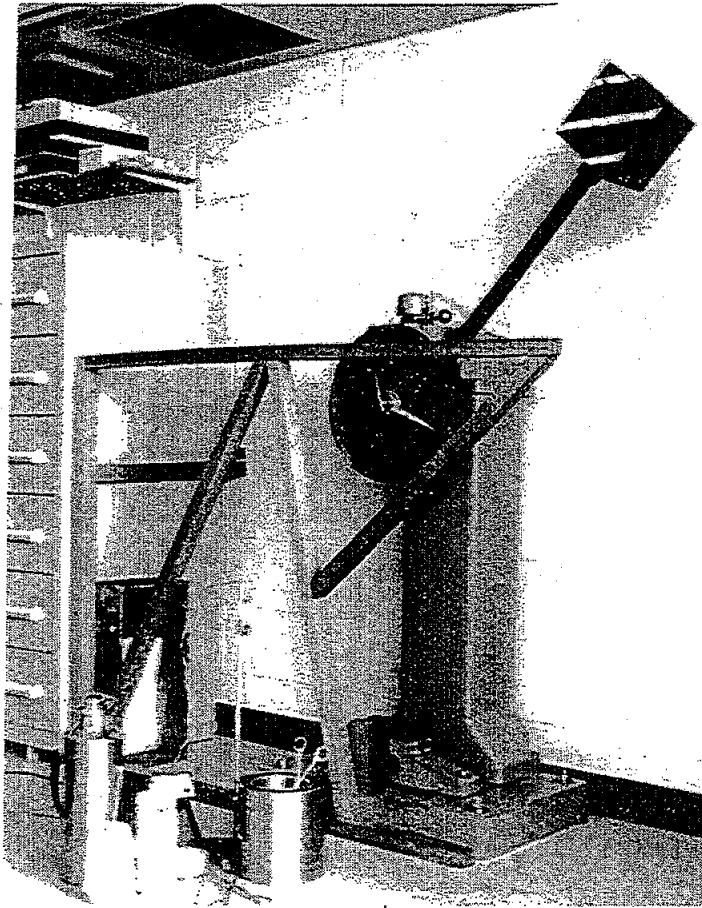


Figure 43. General view of Charpy impact testing machine.

cannot directly be applied to actual structures because the test uses a standard size specimen and an arbitrary notch which are not necessarily representative of real structures. The test is simply used to establish that a specified minimum property level has been achieved. These minimum levels may be based on historical performance or on correlations with full scale tests.

In carrying out a test, the specimen is loaded into the anvil with a pair of special tongs which facilitate location of the specimen in the machine. The specimen is supported at each end as shown in Fig. 44 and the pendulum strikes the back of the specimen behind the notch. This puts the side with the notch into tension, causing the specimen to fracture from the notch.

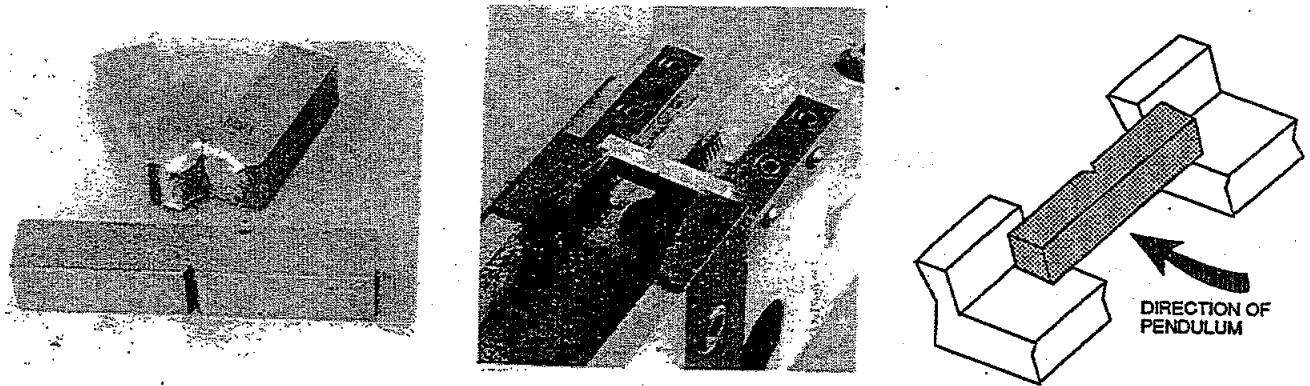


Figure 44. (a) Charpy V-notch (CVN) specimens, (b) Specimen in position, (c) Directions of impact.
 KNOW THESE DIMENSIONS

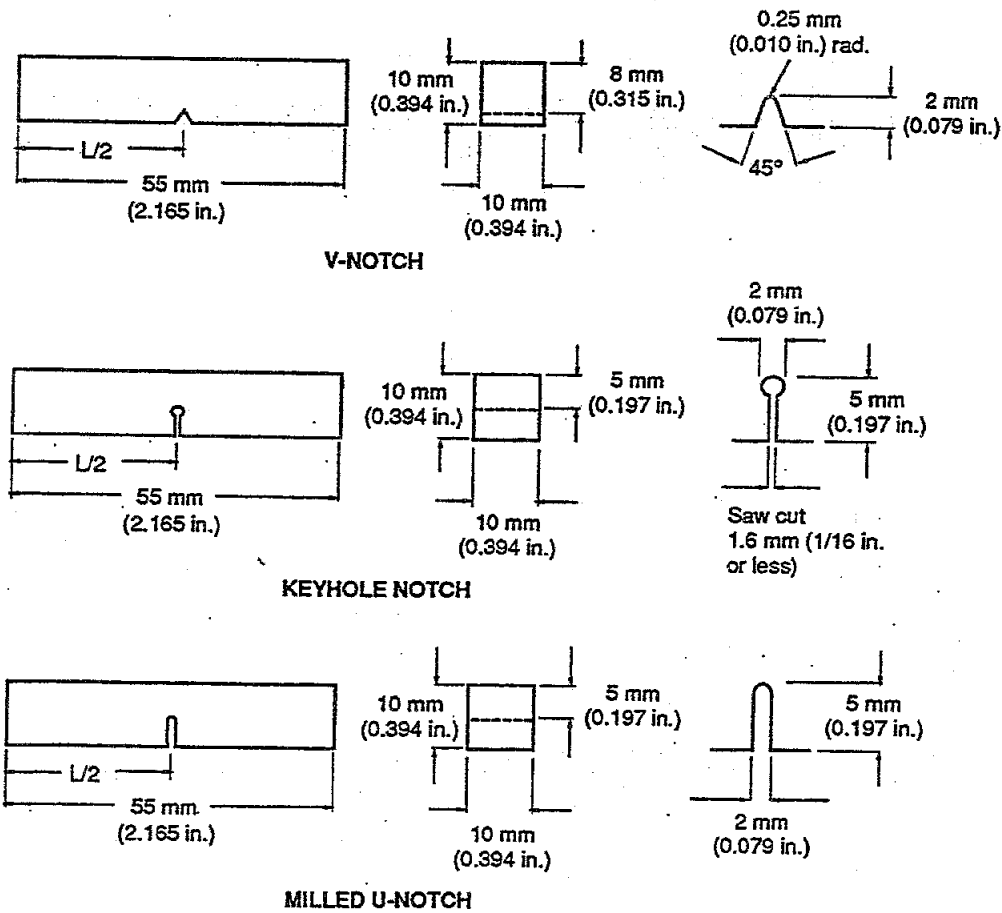


Figure 45. Dimensions of Charpy specimens. The V-notch is the one most commonly used.

The most commonly used specimen, the Charpy V-notch (CVN), is $10 \times 10 \times 55$ mm and has a V-notch 2 mm deep with a 0.25 mm tip radius. Subsize specimens are also sometimes used when testing thinner material. Other shapes of notches, the keyhole and the U-notch, have also been used and are more suited to brittle materials such as cast iron. The dimensions of these specimens are shown in Fig. 45. The dimensions of the notch, in particular, must be carefully controlled and tolerances and finishes are specified in ASTM E23 "Standard Methods for Notched-Bar Impact Testing of Metallic Materials."

A similar test to the Charpy is the Izod impact test. A similar specimen is used, but it is struck by the pendulum in a different manner. Fig. 46 illustrates the essential features of the Izod test.

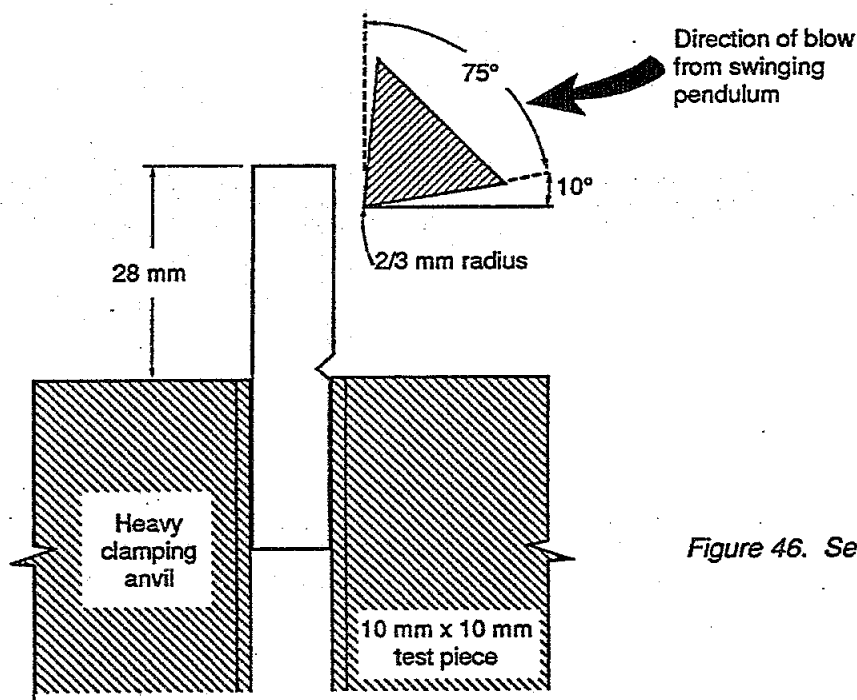


Figure 46. Setup for Izod test.

Measurements from an impact specimen

In addition to the total energy required to fracture the specimen, several other important pieces of information may be obtained from the test. If the fractured ends are examined, it is seen that brittle specimens breaking with low energy have a flat, crystalline fracture showing many shiny facets. A tough specimen shows more deformation and the surface is dull and fibrous. Typically, a specimen would show part of the surface crystalline and part dull. The percentage of crystalline and percentage of dull (known as shear) can be measured.

With tough specimens the side faces also expand opposite the notch and the amount of the deformation can be measured. This is termed the lateral expansion and a device for measuring it is shown in Fig. 47. The lateral expansion is the sum of the expansion on each side.

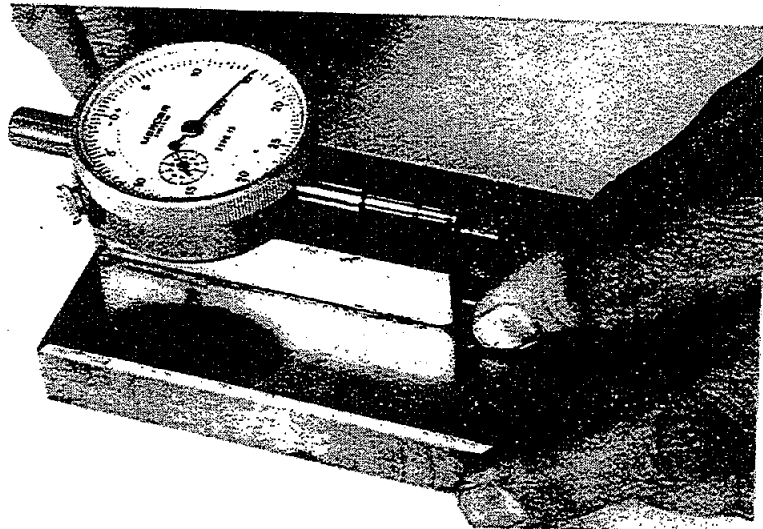


Figure 47. Lateral expansion measurement.

The two broken halves are placed back-to-back and pressed against the stop to measure the expansion of one side. The sum of the expansion on each side is the lateral expansion.

The transition curve

Steels usually become more brittle at low temperatures and this behaviour may be revealed by conducting tests at several temperatures. The energy recorded at each temperature may then be plotted against the temperature. As an example, Fig. 48 shows the results of testing at eight different temperatures. The graph shows low energy at low temperatures, then an increase in energy through a temperature interval known as the transition range. At high temperatures the curve flattens out to give an upper shelf. The transition temperature, at which a certain energy (for example 20 J) is reached, is often used as a method of comparing the toughness of several materials.

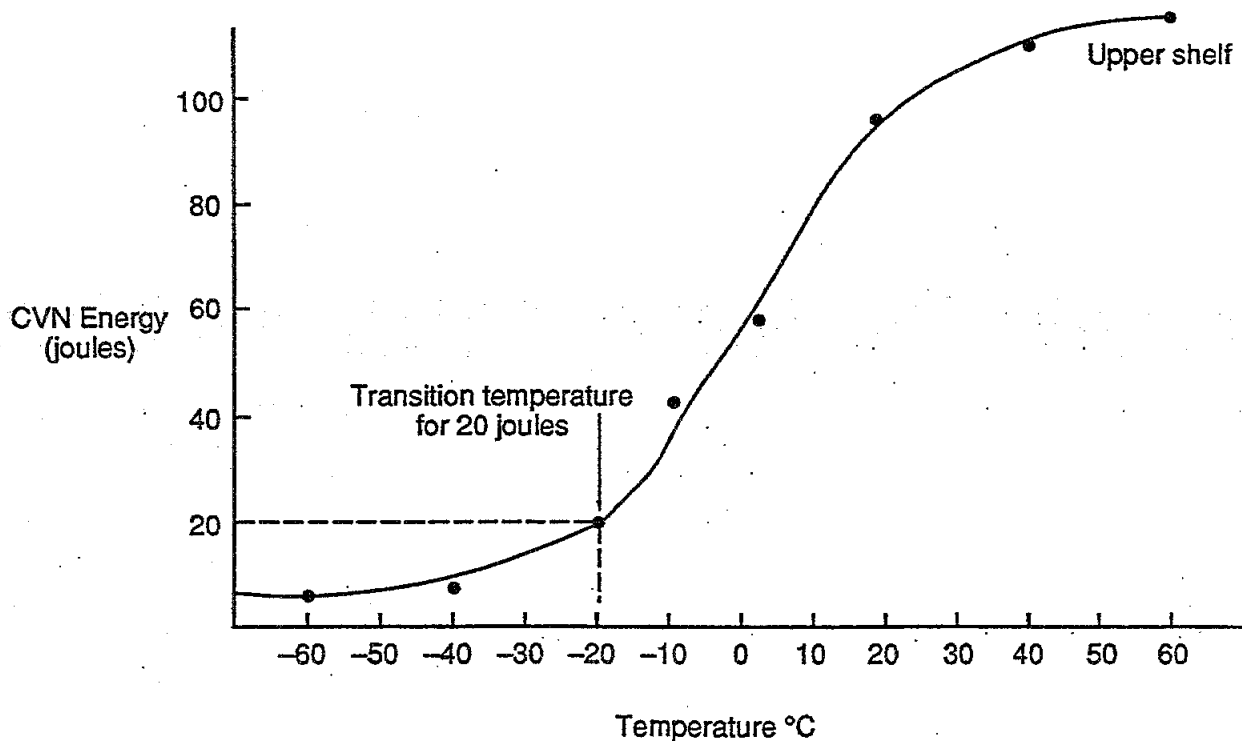
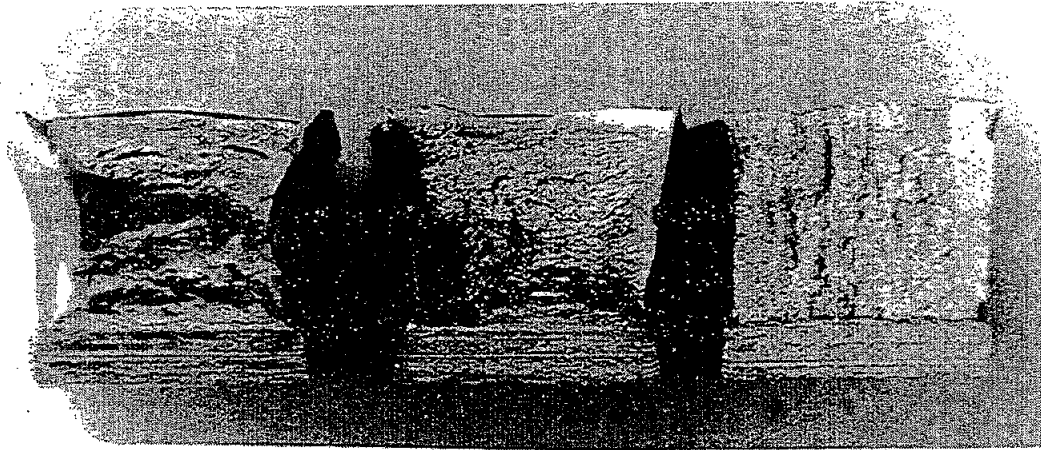


Figure 48. Fracture faces of CVN specimens tested at various temperatures and the transition curve.

Impact testing of welds

When conducting impact tests on welds, it is most important that the specimens are machined from the right location, and that the notch is orientated correctly. A totally misleading result may be obtained if the notch is in the wrong position. When impact tests are required as part of the classification of an electrode, they are machined from the same test weld as the tensile specimens. The test plate is 20 mm and the impact specimens are located mid-thickness as shown in Fig. 49. The notch is placed perpendicular to the plate surface on the centreline of the weld.

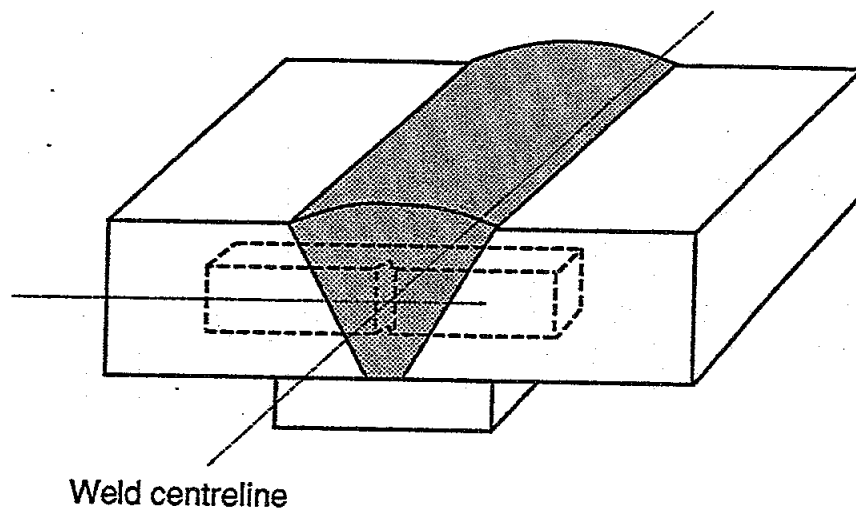


Figure 49. Orientation of impact specimen for weld metal tests.

It is important to note that the width of the specimen probably encompasses more than one weld pass, and the proportion of each pass sampled is likely to affect the results. A slight shift in the location of the specimen, or a small change in the sequence of weld passes, may well have a significant effect on the result of the impact test. When testing to a specification, strict adherence to the given procedures is essential.

The testing of the heat affected zone (HAZ) can be more troublesome because of its narrow width and the fact that it is usually sloping. In most cases, the notch samples only part of the HAZ. To locate the position the specimens should be machined as over-length blanks, then etched to reveal the weld and HAZ. The desired position of the notch can then be marked and the specimens cut to final length. Fig. 50 shows the location of a typical HAZ impact test.

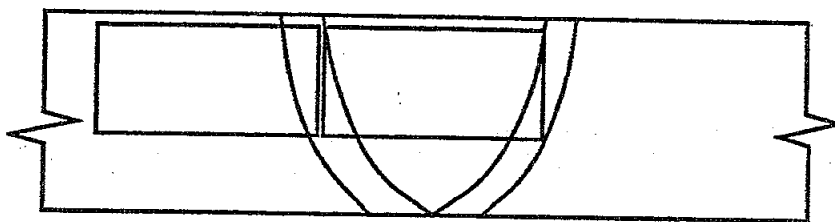
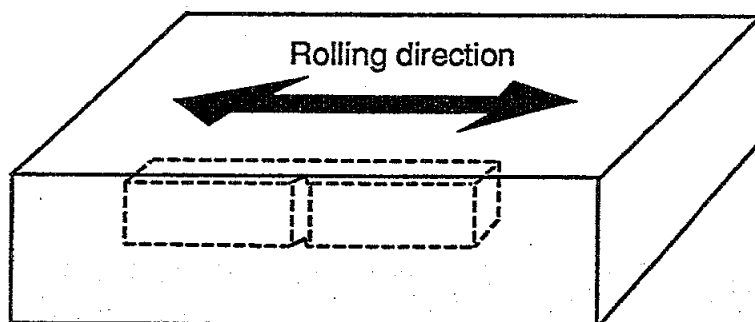


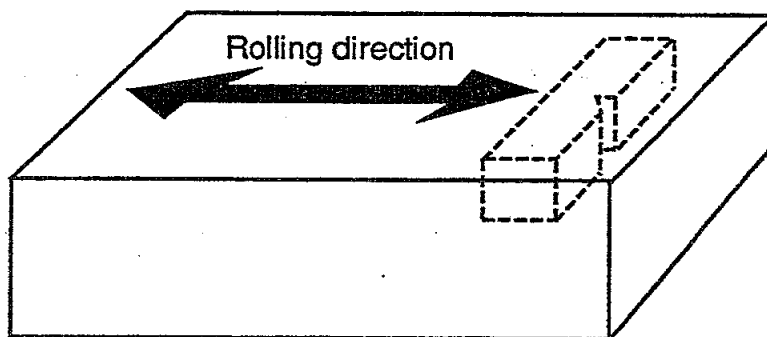
Figure 50. Location of heat affected zone impact specimen.

When impact tests are required in the qualification of welding procedures, specimens from several positions within the joint may be required, particularly for thick plates.

When testing the parent metal, the orientation of the specimen with respect to the rolling direction is important. Usually longitudinal specimens are tested where the length of the Charpy specimen is parallel to the rolling direction. Sometimes (particularly in pressure vessel fabrication) transverse specimens may also be required. These orientations are shown in Fig. 51.



(a) Longitudinal specimen



(b) Transverse specimen

Figure 51. (a) Longitudinal and (b) Transverse Charpy specimens from base metal.

The drop weight test

This test was developed to determine the temperature at which a brittle fracture could initiate in a steel from a small defect. It evolved from observation of fractures in ship steels where fracture initiation occurred from small brittle regions in welds such as arc strikes, tack welds, or cracks in the welds. It is primarily a test for the toughness of the steel, but has been used for measuring toughness of weld metal or the heat affected zone.

The plate being tested has a small weld bead of brittle hard facing metal deposited on it in which a small notch is made. The plate is placed on a jig and a weight dropped on it. This causes the plate to bend against the stop as shown in Fig. 52 and the hard facing bead to crack. This crack may be arrested in the plate, or may lead to complete fracture of the plate. The maximum temperature at which the specimen breaks is known as the "Nil-ductility transition temperature" (NDTT). The method is described in ASTM E208.

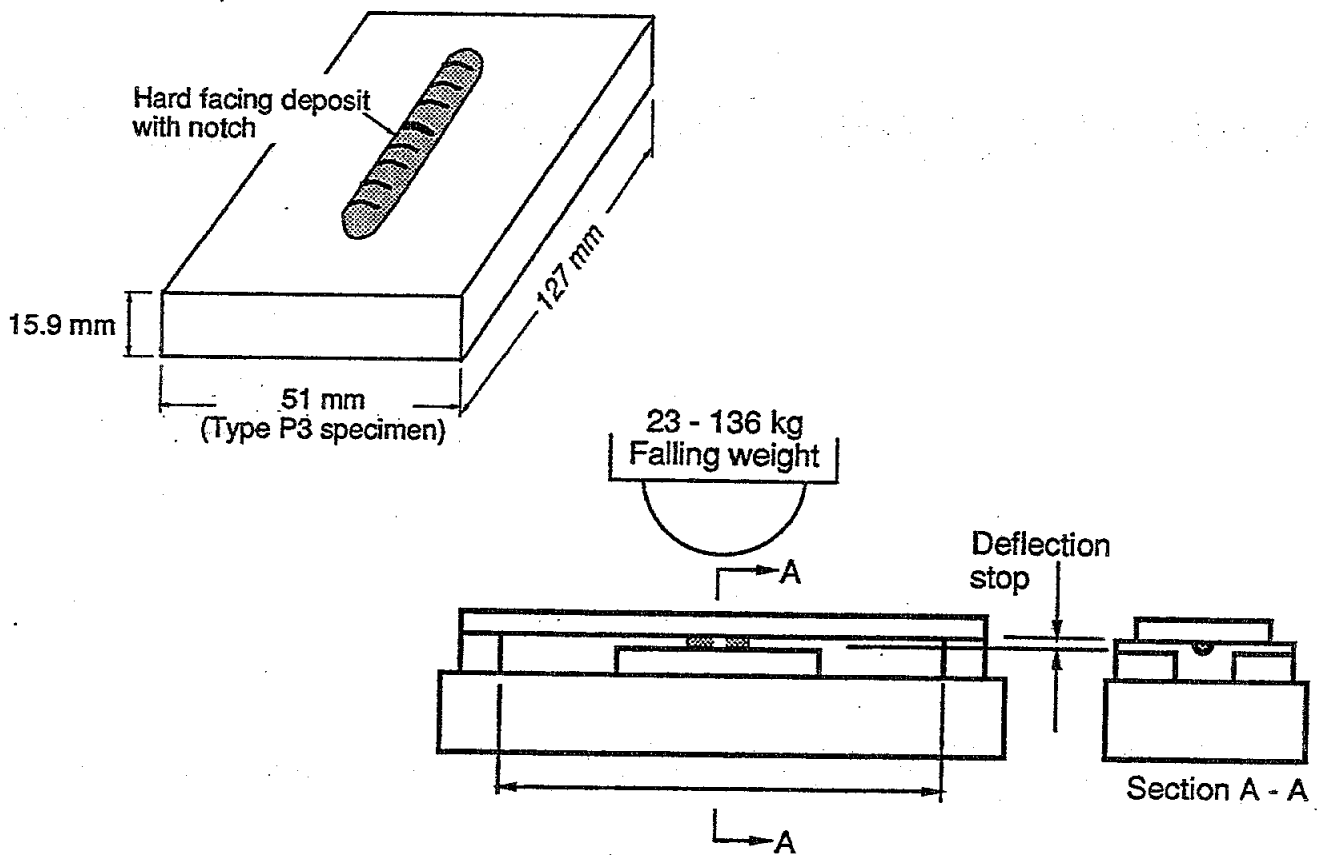


Figure 52. The principle of the drop weight test for determining the Nil-ductility transition temperature (NDTT) of a steel.

Fracture mechanics tests

It was mentioned earlier that the fracture behaviour of a material depended on the presence of notches or cracks. Although empirical tests, such as the Charpy V-notch test, are useful in providing an indication of the toughness of a material, they do not say how large a crack must be to cause brittle fracture. Attempts to relate the size of cracks, material toughness and the stress to cause fracture have evolved into the science of *fracture mechanics*. The main features of fracture mechanics tests are:

- They are initiation tests, i.e., they determine conditions under which fractures initiate.
- They use sharp cracks (usually made by fatiguing the specimen). The crack size is accurately measured.
- The stress or deformation (or both) to cause fracture initiation is measured.

If the stress, " σ ", to cause fracture in a brittle material containing a crack of depth, " a ", is measured, it is possible to calculate a parameter, K_{IC} , known as the critical stress intensity factor. K_{IC} is a measure of the toughness of the material. Knowing the K_{IC} for a material in a structure, and the stress to which it is subjected, allows the maximum size crack that will not cause failure to be determined. A typical specimen for measuring K_{IC} is shown in Fig. 53, and the test method is fully described in ASTM E24.

If the specimen exhibits a significant degree of plastic deformation before fracture (as is the case with most structural steels), a valid K_{IC} cannot be measured. As an alternative for these materials, a method has been developed (principally in the UK) in which the Cracking Tip Opening Displacement (CTOD) is measured. The method is described in a British Standard (B.S. 5762), and is covered by ASTM 1290.

HAS BEEN
T.Q.

* CTOD testing of materials measures the resistance of the material to crack extension and is a function of temperature, thickness, loading rate and microstructure. CTOD data can be used to:

- specify toughness requirements for a structure
- assess the significance of flaws within a structure
- specify the largest acceptable flaw size within a structure and
- assess the sensitivity of a structure to the presence of flaws.

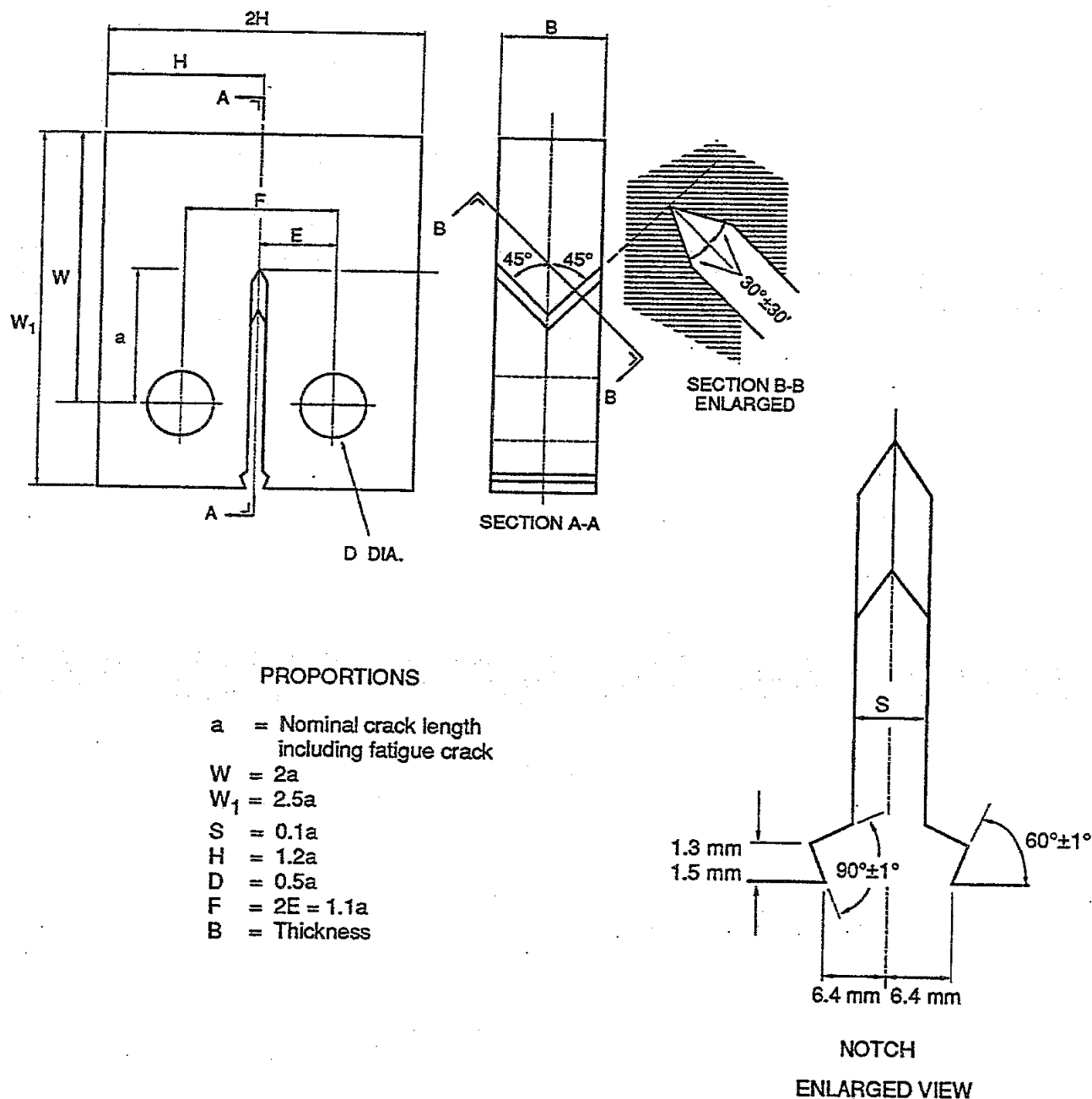


Figure 53. Specimen for measuring K_{IC} of a material.

The CTOD approach is based upon the elastic-plastic stress analysis techniques and unlike Charpy impact testing, the results can be directly applied to welded structures. Furthermore, the data can be used in the design stages, during fabrication and non-destructive inspection, and after the structure is in service.

The test uses specimens whose size is determined by the thickness of the material of interest. A fatigue crack is grown into the area to be tested, either the weld metal, the heat affected zone or the base metal and the specimen is subjected to three point bending. The bending rate is slow and the specimen is tested at the design temperature of the structure. The information obtained from the test is used to perform what is known as an engineering critical assessment. Fig. 54 shows the dimensions of the specimen, where B is the thickness of the material being tested, and the clip gauge used to measure the crack tip opening during the test.

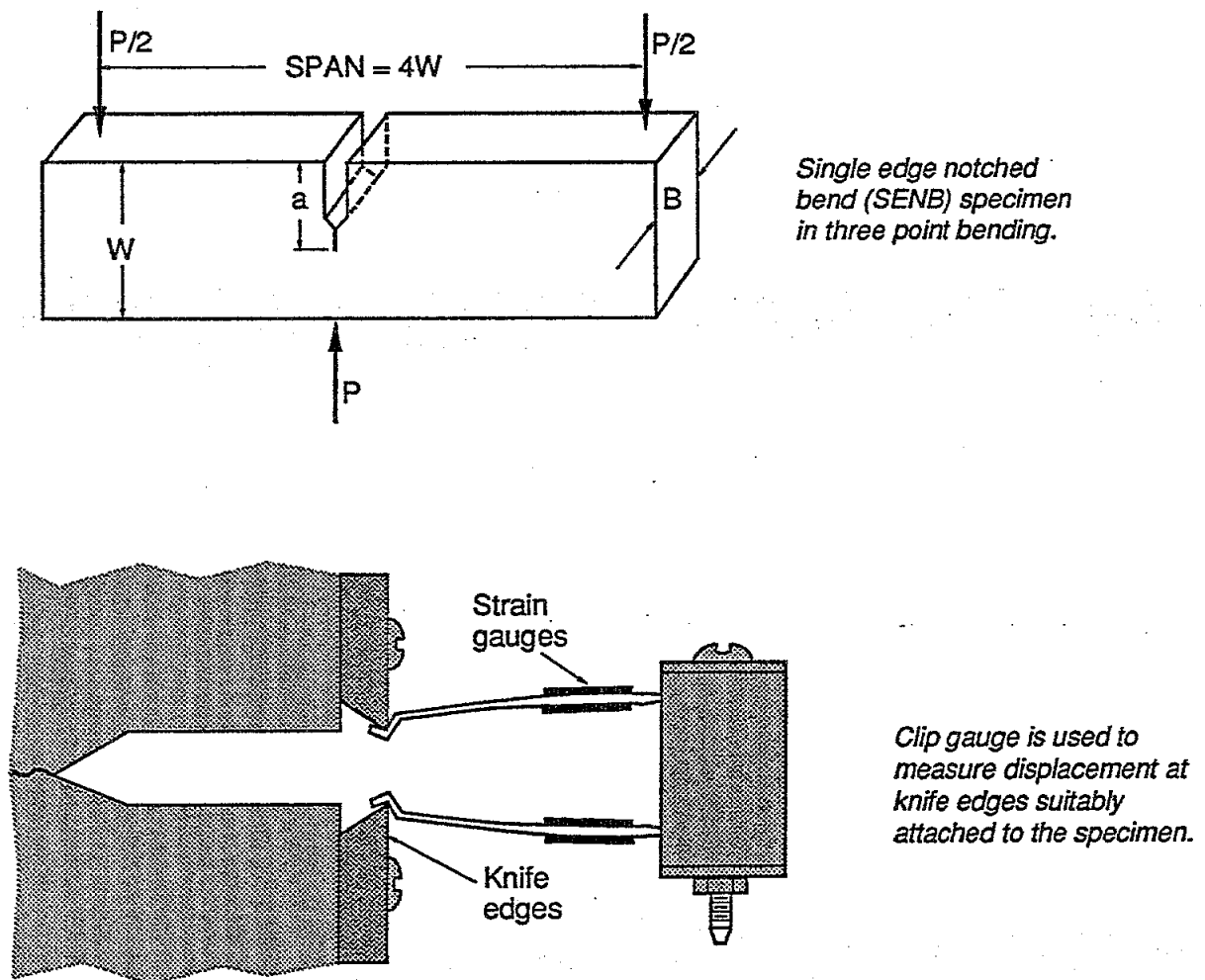


Figure 54. The crack-tip opening displacement (CTOD) test.

PROOF TESTS

Proof testing involves an overload test on a total structure including the welded joints and base metal. It is a final check, not only on the qualities of the welds and material, but also on the effectiveness of the design and thus on the overall efficiency of the weldment. It comes the closest of any test to proving the usefulness of the product for the service intended. Other tests are a means of quality control throughout manufacture. Proof tests are a measure of the final quality as manufactured.

Several difficulties are inherent in overload testing. One is to truly duplicate or nearly simulate actual working conditions, and the other is the possible damage to the weldment which may result from overloading. It is, for example, possible to initiate a minor crack by overload which may well propagate under the lesser loads of service conditions. Sometimes it is advisable to paint the weldment with a resin or other telltale coating that will reveal points at which stress had been carried beyond the yield. This might conceivably occur at abrupt changes of section due to weld faults like overlap, undercut, excessive convexity, or cracks. In this manner, it will also reveal similar design faults.

For vessels and pipes it is usual to test with water. Air, because it can be compressed, involves a danger of explosion and hence is generally not recommended for proof testing. Fig. 55 shows a proof test of a pressure vessel.

The use of water is preferable to air but is slower, and due to its weight, may in some cases induce unintended loading. Clean water at ambient temperature is mostly used for proof tests of this kind. A lower temperature may cause sweating and make examination more difficult. Cold water may also lower toughness and cause brittle fracture. Bleeder valves should be provided at the highest point of the vessel, or pipe system, to permit venting out of all air during the filling operation. The hydrostatic pressure should be applied gradually and should be left on for a sufficient length of time to permit making a complete examination of all welds. The testing pressure is usually called for by the governing code, specification, or drawing. Failing specific instructions, it is usual to test at a pressure one and one-half times the maximum working pressure of the vessel.

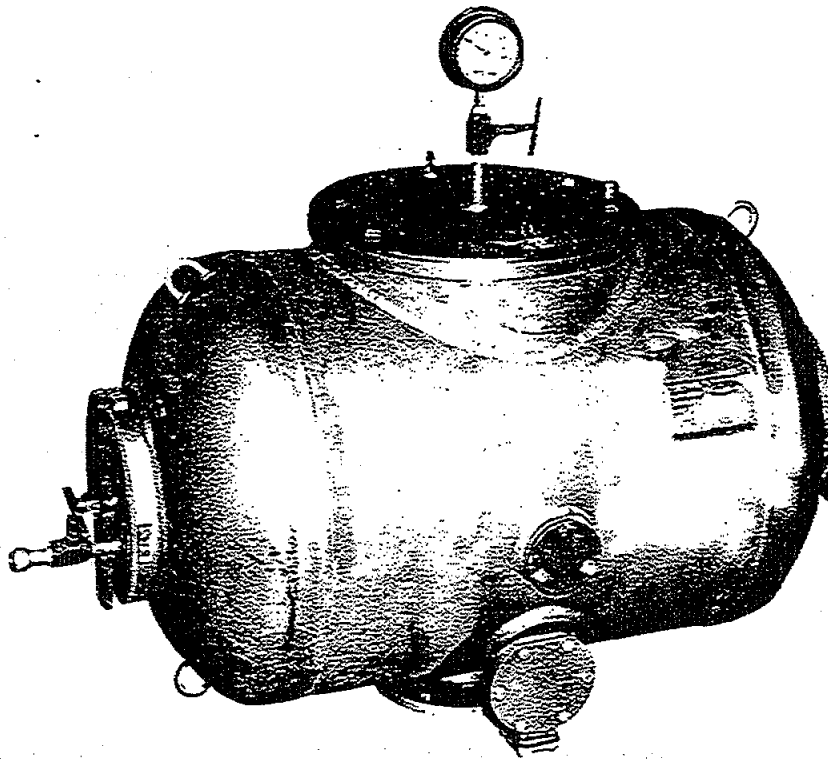


Figure 55. Proof test at 4.14 MPa (600 psi) on a pressure vessel (breaker tank for high voltage switching).

In testing structures such as roof trusses and bridges, a dead weight load of sand bags, pig iron, or standard steel sections may be applied in a distributed manner to simulate actual loading across the span, including both dead weight and wind load. The resulting deflection can be measured and, if desirable, stresses checked at possible points of stress concentration as previously suggested. Hydraulic jacks provide another means of loading and, for such structures as bridges, rolling and shock loads may be applied to better approach actual operating conditions.

For rotating parts such as rotors and turbines, the proof test usually consists of running at an abnormally high speed which will, of course, increase the centrifugal stresses beyond those of normal operation.

A successful overload test is usually a satisfaction to the owner and to the fabricator. It is not an absolute proof of quality or efficiency and it may fall short of proving ability for service. It is a desirable test if not carried to an extreme, but is no substitute for inspection and quality control throughout fabrication.

FATIGUE TESTS

Fatigue failure occurs under repeating or fluctuating loads even though the maximum stress developed is less than the yield and tensile strength of the material. Fatigue failures are progressive, beginning as minute cracks that grow under the action of fluctuating stress.

Sharp notches cause concentrations of stress at a local point and are highly undesirable under fatigue loading. Defects in material and weld faults, such as overlap, undercut, voids, inclusions and microcracks, can lead to fatigue failures. A fatigue crack may be created and failure of the welded joint, or even the complete weldment, may result. Tests have shown that surface contour and weld faults occurring on the surface have a far greater effect on fatigue strength than subsurface defects.

Although fatigue tests are not actually routine tests and are rather too laborious to be carried out under ordinary shop or field conditions, they are, however, of great value for a designer in determining the endurance of welded joints.

The purpose of such tests is to establish the fatigue strength for a given welded joint simulating service conditions. The following methods are used for fatigue testing:

1. A rotating test specimen is subjected to a definite stress in tension and compression ranging from zero to a maximum with each revolution.
2. Bending test. A specimen is subjected to fluctuating stresses of certain magnitude.
3. The push-pull method. A specimen is subjected to alternate and equal values of tension and compression.

There are many types of fatigue testing machines on the market. A special unit for weld tests is shown in Fig. 56 and typical butt joint specimens in Fig. 57. Fillet welds and other types of joint may also be investigated. A large machine is shown in Fig. 58.

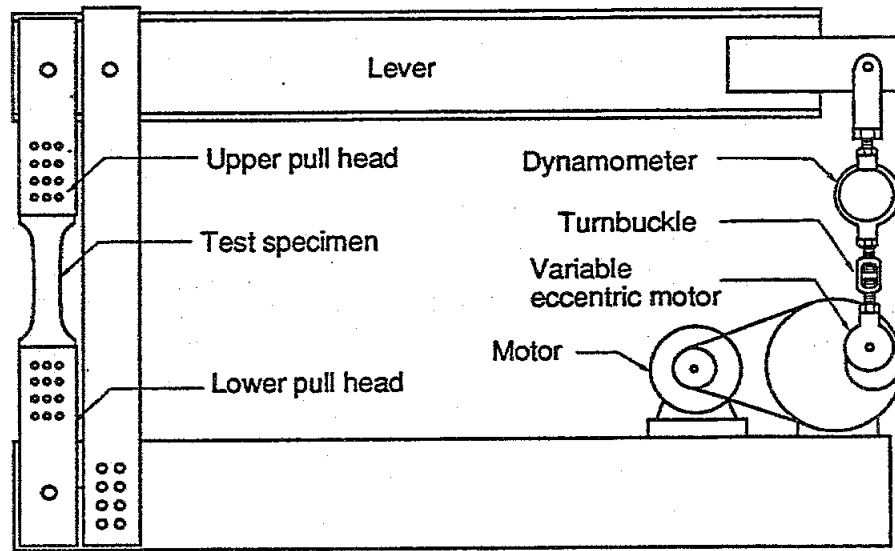


Figure 56. Schematic diagram of Wilson fatigue testing machine

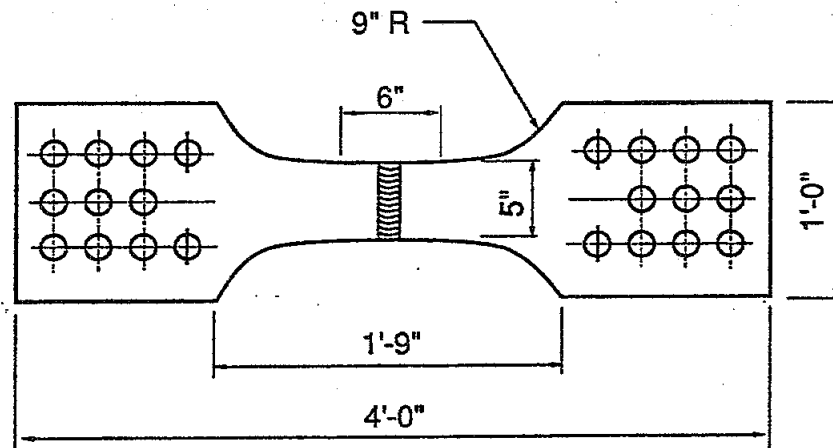


Figure 57. Transverse butt joint fatigue specimen.

It is usual to carry out several tests in which the number of cycles to failure under given stress ranges is determined. A curve of stress range against cycles to failure (an S-N curve) can be plotted. Data of this type have been compiled for various kinds of welded joint details and are included in codes such as CSA W59 and AWS D1.1. A typical S-N curve for a particular joint detail is shown in Fig. 59.

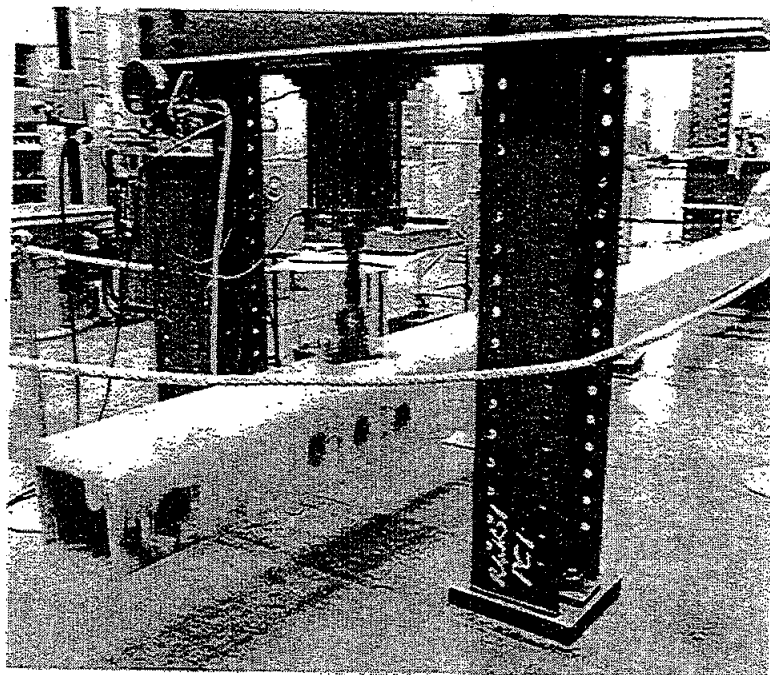


Figure 58. FLAWS (Floor Loading and Weighing System) test frame being used to perform fatigue test on a hollow beam (Ontario Hydro Research Laboratory).

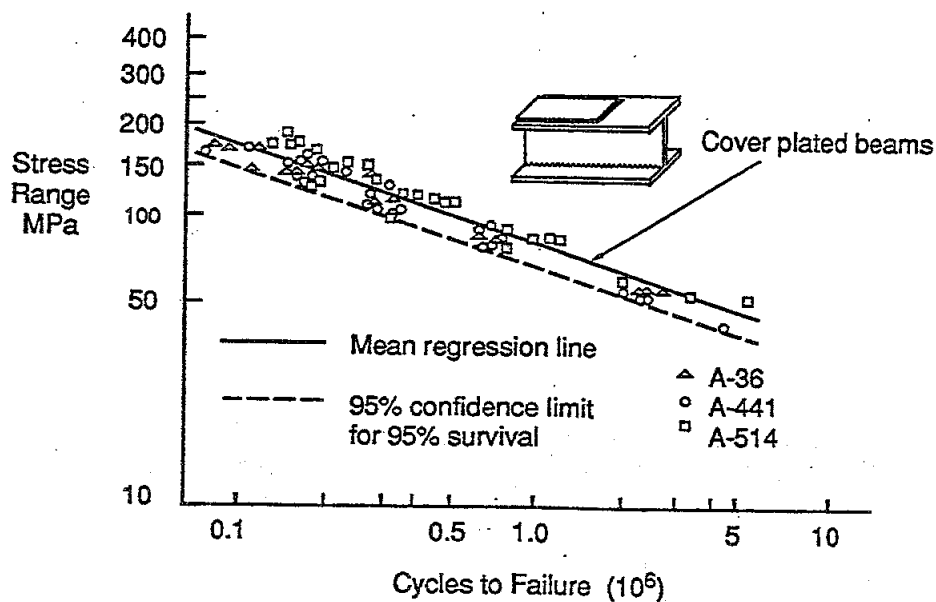


Figure 59. Typical experimental results from fatigue tests on cover plated beams.

Mechanical Testing of Welds

GUIDES AND EXERCISES

MODULE 12

MECHANICAL TESTING OF WELDS

MECHANICAL TESTING OF WELDS

MODULE 12

Guides & Exercises

To obtain maximum benefit from this module we suggest that you follow this guide and complete the exercises as indicated. It is important that you work through the text methodically, studying each section thoroughly before moving on. The exercises are designed to give you an indication of whether you have learned the material and can move on or whether you need to go back and study the section again.

Do the exercises honestly. They will not help you unless you take them seriously. If you get a question wrong go back through the text until you understand where you have gone wrong and know the correct answer.

The length of time required to complete the module will vary from student to student. Find your own pace. Do not rush. Remember you are trying to learn something, not win a race.

Some people like to underline sections when they read a text. We suggest that you use caution if you do this. What you think is important first time you read it may be different after reading it three times. We suggest you read a section three times thoroughly before highlighting anything.

The last exercise is designed to give you an indication of whether you are ready to take the closed-book exams. The exercise questions are of a similar standard to the official exams. Do not take the exam until you feel you are ready and you may wish to study several Modules before taking the exams on each. The details of the examination procedures are on a separate sheet.

If you have any difficulties with this Module do not hesitate to ask for help. You may find you learn more by attending seminars which are given periodically, and you should also contact your local WIC Chapter to see if they can be of assistance. Remember, if you fail the examination you can always try again later.

Guide 1

Read carefully pages 1 to 7 and answer the following questions:

1. Complete the following sentence—

"When a metal is subjected to load it will be resisted by internal forces within the metal. The intensity of these forces through a given plane is known as"

2. Select the three ways in which a load can act on a cross-sectional area in a body.

- a) Perpendicular
- b) Tension
- c) Angular
- d) Compression
- e) Heliaxial
- f) Shear

3. True or false?

"Strain is the extension divided by the original length."

4. The Modulus of Elasticity, "E", for steel is usually taken as—

- a) 2 000 MPa
- b) 200 000 MPa
- c) 200 MPa
- d) 2 000 000 MPa
- e) 29 000 MPa

Mechanical Testing of Welds

Guide 2

Read carefully pages 8 to 22 and answer the following questions:

1. If a plot of stress against strain is made for a bar that undergoes plastic deformation, the stress at which a permanent set is first recorded when the bar is unloaded is known as—
 - a) Permanent set
 - b) Strain
 - c) Elastic limit
 - d) Proportional limit
2. True or false?
"Stress is the load divided by the original cross-sectional area."
3. Complete the following statement—
"To carry out tensile tests, special machines are needed in order to exert the necessary force. They are generally of two types..... and....."
4. Complete the following sentence—
"If it is desired to measure the strain during a test, an.....is placed on the specimen."

Guide 3

Read carefully pages 23 to 29 and answer the following questions:

1. Name the three types of guided bend tests.

2. Complete the following statement—

“After bending, the welds are examined for flaws or cracks. It is a condition of almost all codes that the specimens shall be considered to have failed if, on examination of the convex surface after bending, there is a crack or open defect exceedingmm in length measured in any direction”

3. What is the purpose of a nick break test?

Guide 4

Read carefully pages 30 to 37 and answer the following questions:

1. Answer yes or no—

Does a hardness test give any indication of whether the material is readily weldable?

2. Name three types of hardness testing machines.

3. Most hardness testing machines use the indentation test where a penetrator of a given material, shape and size is forced into the surface of the material being tested by a given load. However, one of the machines uses the principle of a bouncing hammer. How does this hardness tester work?

4. In the Rockwell C Scale what is the major load which is used?

- a) 130 kg
- b) 100 kg
- c) 150 kg
- d) 140 kg
- e) 160 kg

5. Complete the following statement—

"It is essential that there be no friction in the loading system of the machine or a load will result."

Guide 5

Read carefully pages 37 to 47 and answer the following questions:

1. When making a hardness test the thickness of the specimen is very important. As a rule, the thickness should be—

- a) Eight times the depth of the impression
- b) Five " " " " " "
- c) Fifteen " " " " " "
- d) Ten " " " " " "
- e) Twenty " " " " " "

2. Complete the following sentence—

"The most common toughness test is the in which a notched specimen is broken by a swinging pendulum and the amount of energy required to break the specimen is recorded."

3. True or false?

"If the fractured ends of an impact test specimen are examined, it is seen that brittle specimens breaking with low energy have a flat crystalline fracture showing many shiny facets."

4. When impact tests are required in the qualification of welding procedures, several positions may be required for particularly thick plates.

Sketch the position of a longitudinal specimen from base metal.

Mechanical Testing of Welds

Guide 6

Read carefully pages 48 to 56 and answer the following questions:

1. True or false?

"The drop weight test is a test for the toughness of the steel and is not used for measuring toughness of weld metal or the heat affected zone."

2. Complete the following statement—

"Attempts to relate the size of cracks, material toughness, and the stress to cause fracture have evolved into the science of"

3. When hydrostatic testing a pressure vessel or pipe, failing special instruction, it is usual to test at a pressure of—

- a) two times the maximum working pressure of the vessel
- b) two and one half times the maximum working pressure of the vessel
- c) one and one third " " " " " " " "
- d) one and one half " " " " " " " "

ANSWERS

Guide 1

1. Stress
2. b), d), f)
3. True
4. b)

Guide 2

1. c)
2. True
3. Mechanical and hydraulic
4. Extensometer

Guide 3

1. a) Face bend b) Root bend c) Side bend
2. 3
3. To reveal internal weld defects

Guide 4

1. Yes
2. Brinell, Rockwell, Vickers
3. The rebound velocity of a tungsten carbide hammer is measured electronically and converted to a hardness value.
4. c)
5. Lighter

Guide 5

1. d)
2. Charpy impact test
3. True

Guide 6

1. True
2. Fracture Mechanics
3. d)

MODULE 12

TEST

This test is designed to determine whether you are ready to attempt the formal examination.

Complete the ANSWER SHEET and compare the results with the TEST KEY. If you score less than 70% we suggest you restudy the material.

1. What is the approximate diameter of the tensile specimen most often used for all-weld metal tests?
 - a) 20 mm
 - b) 1 in.
 - c) 5 mm
 - d) 10 mm
 - e) 3.8 in.
2. High hardness values on steel can generally be related to:
 - a) high strength and low ductility
 - b) a high percentage of alpha ferrite constituent
 - c) low strength and high ductility
 - d) high strength and high ductility
 - e) an increased degree of weldability
3. The nil-ductility transition temperature determined from a drop weight test refers to:
 - a) the lowest temperature at which a crystalline fracture surface is observed
 - b) the Charpy transition temperature
 - c) the minimum temperature at which the specimen breaks
 - d) the upper shelf
 - e) the maximum temperature at which the specimen breaks
4. When a 30 m long steel cable supports an axial load, there is a strain of 0.25%. The elongation of the cable with this load is:
 - a) 150 mm
 - b) 6 mm
 - c) 75 mm
 - d) 1 m
 - e) 7.5 m

5. The modulus of elasticity (E) of steel is:
- a) 2 900 000 MPa
 - b) 200 000 MPa
 - c) 20 000 000 ksi
 - d) 29 000 000 MPa
 - e) 2 900 000 psi
6. Impact tests measure the:
- a) hardness of a material
 - b) ultimate tensile strength of a material
 - c) ability of a material to store energy
 - d) energy required to break a specimen
 - e) load required to break a specimen
7. A guided root bend test on a weld would best reveal:
- a) the weld ductility by measuring the difference in distance between gauge marks
 - b) excessive reinforcement
 - c) the integrity of the face weld
 - d) lack of penetration or fusion
 - e) HAZ properties
8. Charpy test values:
- a) are a measure of ductility
 - b) measure tensile strength
 - c) can be applied directly to a real structure
 - d) are used for qualification and quality control checks
 - e) provide the same results as drop weight tests
9. A steel bar of square cross-section, 50 mm × 50 mm is subjected to a load of 213 kN. What is the tensile stress in the bar:
- a) 852 ksi
 - b) 213 MPa
 - c) 85.2 MPa
 - d) 8.52 MPa
 - e) 213 ksi
10. When conducting a tensile test the rate of loading up to the yield point is usually limited to some maximum value. Why?
- a) because a fast loading rate might increase the yield stress
 - b) because a fast loading rate might lower the UTS
 - c) to prevent the specimen breaking before reaching the UTS
 - d) to allow time for readings to be taken
 - e) to allow time for hydrogen removal

Mechanical Testing of Welds

Canadian Welding Bureau Answer Sheet - Module 12

Complete the "Answer Sheet" and compare the results with the "Test Key". If you have a pass mark less than 70%, you are advised to re-study the material.

Please circle only ONE letter corresponding to the answer you think is most correct.

QUESTION	ANSWERS				
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e

The answer key below is provided for your use in the event that you wish to retest yourself.

QUESTION	ANSWERS				
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e

Canadian Welding Bureau
Test Key - Module 12

Compare your answer sheet to this key.

QUESTION	ANSWERS				
1	a	b	c	(d)	e
2	(a)	b	c	d	e
3	a	b	c	d	(e)
4	a	b	(c)	d	e
5	a	(b)	c	d	e
6	a	b	c	(d)	e
7	a	b	c	(d)	e
8	a	b	c	(d)	e
9	a	b	(c)	d	e
10	(a)	b	c	d	e

