# Mechanical testing - Tensile testing, Part 1

Mechanical testing is carried out to produce data that may be used for design purposes or as part of a material joining procedure or operator acceptance scheme. The most important function may be that of providing design data since it is essential that the limiting values that a structure can withstand without failure are known.

Fig.1. Typical tensile testing machine

Inadequate control of the material properties by the supplier, or incompetent joining procedures and operatives are, however, equally crucial to the supply of a product that is safe in use. An example of this dual role of mechanical testing is the tensile test that may be used either to determine the yield strength of a steel for use in design calculations or to ensure that the steel complies with a material specification's strength requirements.

Mechanical tests may also be divided into *quantitative* or *qualitative* tests. A quantitative test is one that provides data that will be used for design purposes, a qualitative test where the results will be used for making comparisons - hardness or Charpy-V tests - for example as a 'go/no go test' such as the bend test.

Mechanical property data are obtained from a relatively small number of standard tests and these will be covered over the next several articles. These will include tensile and toughness tests, the tests used for welding procedure and welder approval and those used for the determination of in-service properties.

## Tensile testing

As mentioned earlier the tensile test is used to provide information that will be used in design calculations or to demonstrate that a material complies with the requirements of the appropriate specification - it may therefore be either a quantitative OR a qualitative test.

The test is made by gripping the ends of a suitably prepared standardised test piece in a tensile test machine and then applying a continually increasing uni-axial load until such time as failure occurs. Test pieces are standardised in order that results are reproducible and comparable as shown in *Fig 2*.

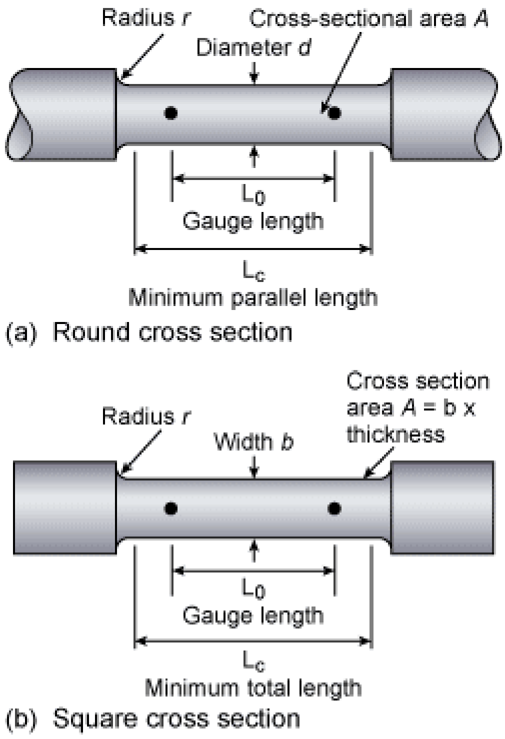



Fig. 2. Standard shape tensile specimens

Specimens are said to be *proportional* when the *gauge length*, $L_0$, is related to the original cross sectional area, $A_0$, expressed as $L_0 = k\sqrt{A_0}$. The constant k is 5.65 in EN specifications and 5 in the ASME codes. These give gauge lengths of approximately 5x specimen diameter and 4x specimen diameter respectively – whilst this difference may not be technically significant it is important when claiming compliance with specifications.

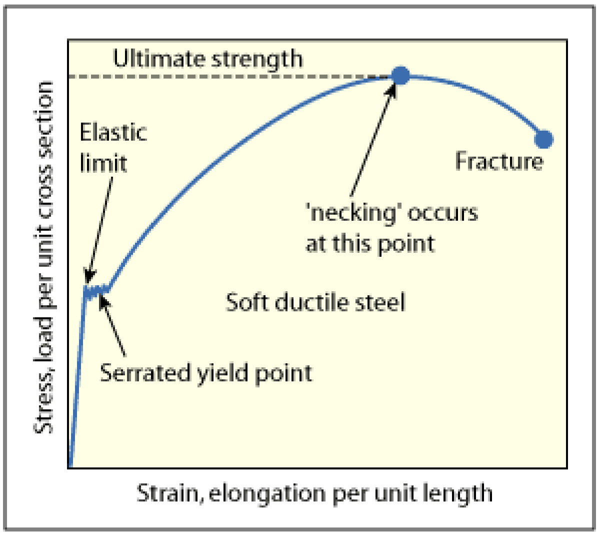



Fig. 3. Stress/strain curve

Both the load (stress) and the test piece extension (strain) are measured and from this data an *engineering stress/strain curve* is constructed, *Fig. 3*. From this curve we can determine:

a) the *tensile strength*, also known as the *ultimate tensile strength*, the load at failure divided by the original cross sectional area where the ultimate tensile strength (U.T.S.), $\sigma_{max} = P_{max}/A_0$, where $P_{max}$ = maximum load, $A_0$ = original cross sectional area. In EN specifications this parameter is also identified as '$R_m$';

b) the *yield point* (YP), the stress at which deformation changes from elastic to plastic behaviour ie below the yield point unloading the specimen means that it returns to its original length, above the yield point permanent plastic deformation has occurred, YP or $\sigma y = P_{yp}/A_0$ where $P_{yp}$ = load at the yield point. In EN specifications this parameter is also identified as '$R_e$';

c) By reassembling the broken specimen we can also measure the *percentage elongation*, El% how much the test piece had stretched at failure where El% = $(L_f - L_0/L_o)$ x100 where Lf = gauge length at fracture and L0 = original gauge length. In EN specifications this parameter is also identified as 'A' ( *Fig. 4a*).

d) the *percentage reduction of area*, how much the specimen has necked or reduced in diameter at the point of failure where R of A% =$(A_0 - A_f/A_0)$ x 100 where $A_f$ = cross sectional area at site of the fracture. In EN specifications this parameter is also identified as 'Z', ( *Fig. 4b*).

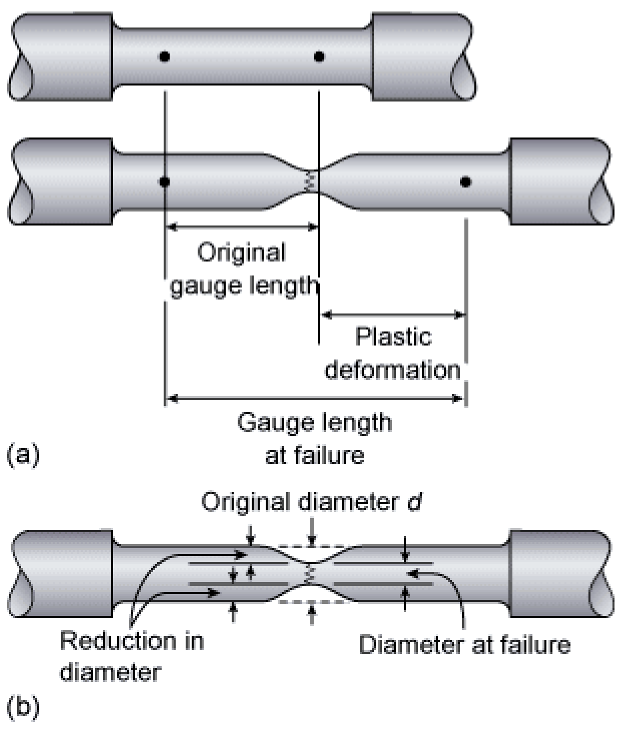



Fig.4
a) Calculation of percentage elongation
b) Calculation of percentage reduction of area

(a) and (b) are measures of the strength of the material, (c) and (d) indicate the *ductility* or ability of the material to deform without fracture.

The slope of the elastic portion of the curve, essentially a straight line, will give *Young's Modulus of Elasticity*, a measure of how much a structure will elastically deform when loaded.

A low modulus means that a structure will be flexible, a high modulus a structure that will be stiff and inflexible.

To produce the most accurate stress/strain curve an extensometer should be attached to the specimen to measure the elongation of the gauge length. A less accurate method is to measure the movement of the cross-head of the tensile machine.

The stress strain curve in Fig.3 shows a material that has a well pronounced yield point but only annealed carbon steel exhibits this sort of behaviour. Metals that are strengthened by alloying, by heat treatment or by cold working do not have a pronounced yield and some other method must be found to determine the 'yield point'.

This is done by measuring the *proof stress* ( *offset yield strength* in American terminology), the stress required to produce a small specified amount of plastic deformation in the test piece.

The proof stress is measured by drawing a line parallel to the elastic portion of the stress/strain curve at a specified strain, this strain being a percentage of the original gauge length, hence *0.2% proof, 1% proof* (see *Fig.5*).

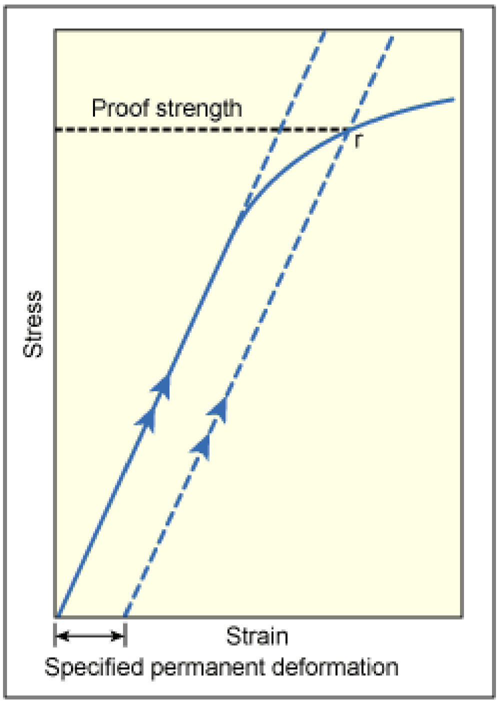



Fig.5. Determination of proof (offset yield) strength

For example, 0.2% proof strength would be measured using 0.2mm of permanent deformation in a specimen with a gauge length of 100mm. Proof strength is therefore not a fixed material characteristic, such as the yield point, but will depend upon how much plastic deformation is specified. It is essential therefore when considering proof strengths that the percentage figure is always quoted. Most steel specifications use 0.2% deformation, $R_{P0.2}$ in the EN specifications.

Some materials such as annealed copper, grey iron and plastics do not have a straight line elastic portion on the stress/strain curve. In this case the usual practice, analogous to the method of determining proof strength, is to define the 'yield strength' as the stress to produce a specified amount of permanent deformation.

Part 2 of this series on mechanical testing will cover welding procedure approval tensile testing.

# Mechanical testing - Tensile testing Part II

## Welding procedure approval for tensile testing.

To approve a butt welding procedure most specifications such as BS EN 288 Parts 3 and 4 and ASME IX require tensile tests to be carried out.

These are generally cross joint (CJ) tensile tests of square or rectangular cross section that, as the name suggests, are oriented across the weld so that both parent metals, both heat affected zones (HAZs) and the weld metal itself are tested ( *Fig. 1*). The excess weld metal in the cap of the weld may be left in-situ or machined off.

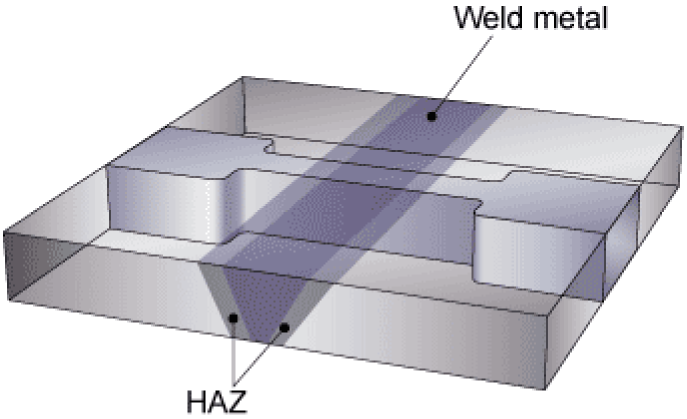



Fig. 1. Square or rectangular cross joint tensile test piece

While it is possible to measure the yield strength, the elongation and the reduction of area of CJ specimens the fact that there are at least three different areas with dissimilar mechanical properties makes such measurements inaccurate and unreliable, although this is sometimes carried out purely for information purposes.

The specifications mentioned above require the UTS and the position of the fracture only to be recorded. The cross joint strength is usually required to exceed the minimum specified UTS of the parent metal. In most situations the weld metal is stronger than the parent metal - it is overmatched - so that failure occurs in the parent metal or the HAZ at a stress above the specified minimum.

In cases where the weld and/or the HAZs are weaker than the parent metal - welded age-hardened or cold worked aluminium alloys are a good example - this is covered in most specifications. Refer to Table 2 of BS EN 288 Part 4 or clause QW153 in ASME IX.

The designer must also take this into account in design calculations and provide some method of compensating for this loss of strength.

The tensile testing of flat plate butt welds presents few problems of specimen shape but those machined from a pipe butt joint are not flat and this curvature can affect the results. In the context of welding procedure approval testing, this is not significant since the test is used only for the determination of the UTS and the position of the fracture. For more accurate results the test piece may be waisted and may be machined flat as illustrated in *Fig. 2*.

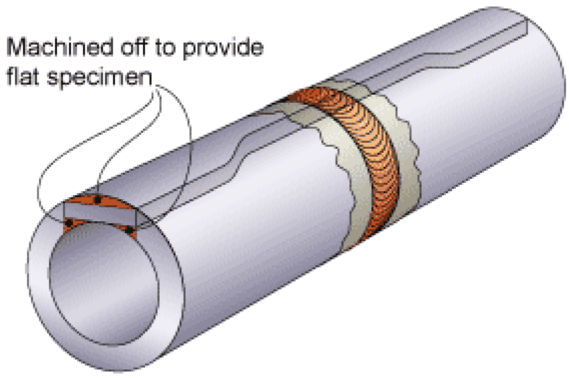
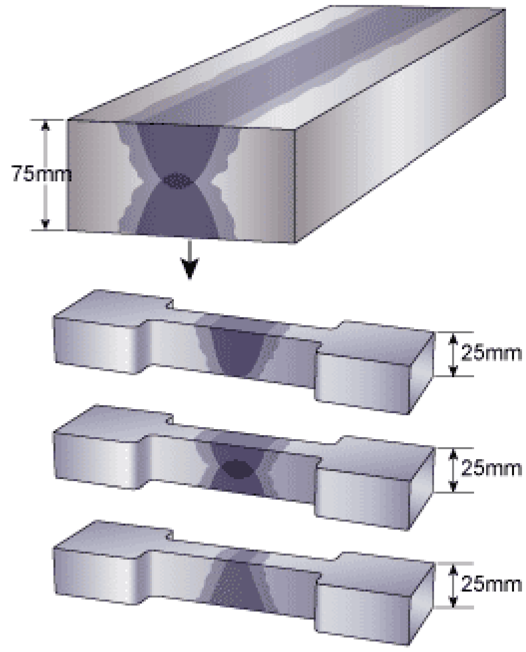



Fig. 2. Flat cross joint tensile specimen machined from tube

It may be necessary to machine a number of specimens through the thickness of a weld, particularly on very thick joints where the capacity of the tensile machine is insufficient to pull a full thickness specimen, *Fig. 3*.

Fig. 3. Multiple cross joint specimens machined from thick plate




To test a small diameter tube, a solid bar is inserted in the bore of the tube to prevent the tube collapsing when the sample is clamped into the tensile machine.

Most weld testing is carried out with CJ specimens but longitudinally oriented specimens are useful particularly where the weld metal or the HAZ is very strong but ductility is low.

In a CJ specimen the parent metal can yield and finally fail without the weld metal or the HAZ experiencing any significant amount of deformation whereas in a longitudinal test piece the load is shared more equally.

A brittle weld or HAZ will not elongate with the parent metal but will crack, with the cracks opening, but not necessarily propagating into the parent metal, as testing proceeds.

The testing described above is that required by the welding procedure approval specifications. These provide no assurance that the welds in a structure will be suitable for their purpose such as elevated or cryogenic service and many application standards such as BS PD 5500 Unfired Pressure Vessels, and ASME VIII Pressure Vessels, require additional tests.

Since the strength of a metal falls as the temperature rises these specifications require elevated temperature tensile tests to be carried out at the maximum design temperature.

These tests are required to be carried out on the weld metal only and use a longitudinally orientated round cross section specimen from which an accurate measurement of the proof strength can be obtained.

Many application standards such as BS PD 5500 require tests additional to those required by, for example, BS EN 288 Part 3. This must be remembered when procedure approval documentation is submitted for approval by the inspecting authority or the client.

## Validity of tensile data.

The samples taken are assumed to be representative of the bulk of the material but this is not always the case.

Tensile strength of a casting, for instance, is often determined from a specimen machined from a riser and this will have a grain size different from that of the bulk of the casting.

A rolled steel plate will be found to have different properties in the longitudinal, transverse and through thickness directions. Material specifications such as BS EN 10028, Flat Products in Steel for Pressure Purposes, therefore, require the tensile test to be taken transverse to the rolling direction so that the steel is tested across the 'grain' - the lower strength, lower ductility direction.

The size of a product can also influence the properties as, during heat treatment, the section thickness will affect the cooling rate with slower cooling rates, and hence softer structures, at the centre of thicker sections. This is dealt with in material standards by specifying what is known as the 'limiting ruling section', the maximum diameter of bar at which the required mechanical properties can be achieved at the centre.

In addition to variations of the properties due to the shape of the specimens and the testing temperature, the rate of loading will also affect the results.

*Figure 4* shows how the tensile strength increases but ductility decreases as the testing speed is increased. The speed of the cross head of the tensile machine therefore needs to be controlled and BS EN 10002 specifies a stress rate range of 6MPa per second to 60MPa per second. The ASTM specifications have similar - but not identical - requirements.

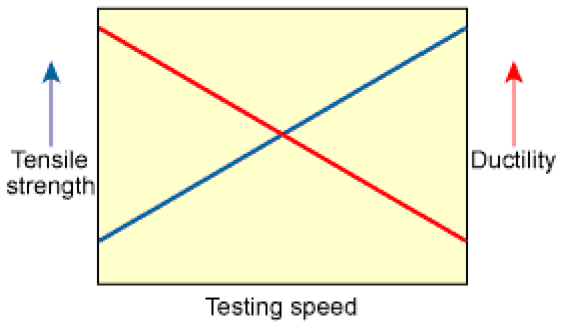



Fig.4. Effect of speed of testing on strength and ductility

Needless to say, calibration of testing equipment to guarantee operation within acceptable parameters is mandatory.

### Relevant specifications

BS EN 10002 Methods of tensile testing of metallic materials.

BS EN 876 Destructive tests on welds in metallic materials - longitudinal tensile test.
BS EN 895 Destructive tests on welds in metallic materials - transverse tensile test.
BS EN ISO 7500-1 Tension/compression testing machines. verification and calibration of the force measuring system.
ASTM A370 Mechanical testing of steel products.
ASTM E8 Tension testing of metallic materials.
ASTM B557 Tension testing wrought and cast aluminium and magnesium alloy products.

This article was prepared by Gene Mathers.

# Mechanical testing - notched bar or impact testing

Before looking at impact testing let us first define what is meant by 'toughness' since the impact test is only one method by which this material property is measured.

Toughness is, broadly, a measure of the amount of energy required to cause an item - a test piece or a bridge or a pressure vessel - to fracture and fail. The more energy that is required then the tougher the material.

The area beneath a stress/strain curve produced from a tensile test is a measure of the toughness of the test piece under slow loading conditions. However, in the context of an impact test we are looking at notch toughness, a measure of the metal's resistance to brittle or fast fracture in the presence of a flaw or notch and fast loading conditions.

It was during World War II that attention was focused on this property of 'notch toughness' due to the brittle fracture of all-welded Liberty ships, then being built in the USA. From this work the science of fracture toughness developed and gave rise to a range of tests used to characterise 'notch toughness' of which the *Charpy-V* test described in this article is one.

There are two main forms of impact test, the *Izod* and the *Charpy* test.

Both involve striking a standard specimen with a controlled weight pendulum travelling at a set speed. The amount of energy absorbed in fracturing the test piece is measured and this gives an indication of the notch toughness of the test material.

These tests show that metals can be classified as being either 'brittle' or 'ductile'. A brittle metal will absorb a small amount of energy when impact tested, a tough ductile metal a large amount of energy.

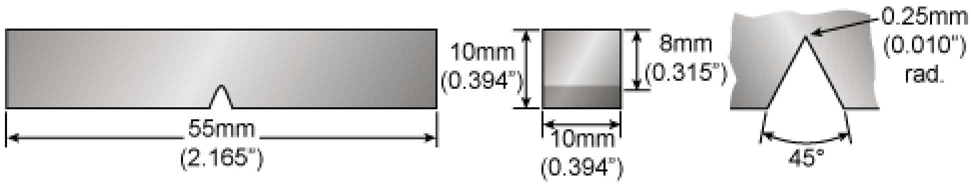
It should be emphasised that these tests are *qualitative*, the results can only be compared with each other or with a requirement in a specification - they *cannot* be used to calculate the fracture toughness of a weld or parent metal.

Tests that can be used in this way will be covered in future *Job Knowledge* articles. The Izod test is rarely used these days for weld testing having been replaced by the Charpy test and will not be discussed further in this article.

The Charpy specimen may be used with one of three different types of notch, a 'keyhole', a 'U' and a 'V'. The keyhole and U-notch are used for the testing of brittle materials such as cast iron and for the testing of plastics. The V-notch specimen is the specimen of choice for weld testing and is the one discussed here.

The standard Charpy-V specimen, illustrated in *Fig. 1.* is 55mm long, 10mm square and has a 2mm deep notch with a tip radius of 0.25mm machined on one face.

Fig. 1. Standard Charpy-V notch specimen




To carry out the test the standard specimen is supported at its two ends on an anvil and struck on the opposite face to the notch by a pendulum as shown in *Fig. 2.* The specimen is fractured and the pendulum swings through, the height of the swing being a measure of the amount of energy absorbed in fracturing the specimen. Conventionally three specimens are tested at any one temperature, see *Fig. 3*, and the results averaged.

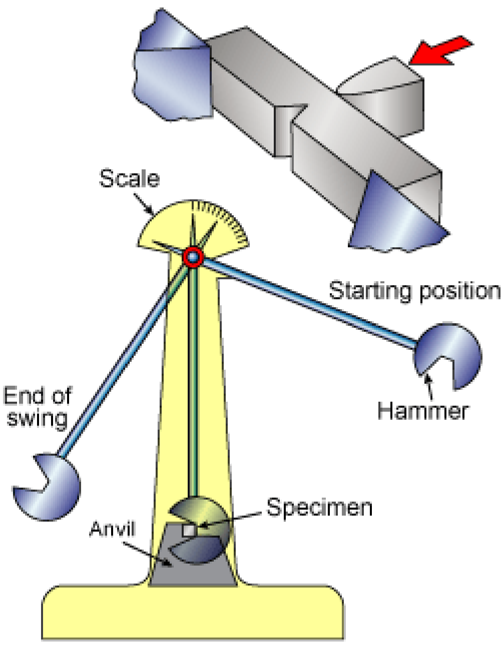



Fig. 2. Charpy testing machine

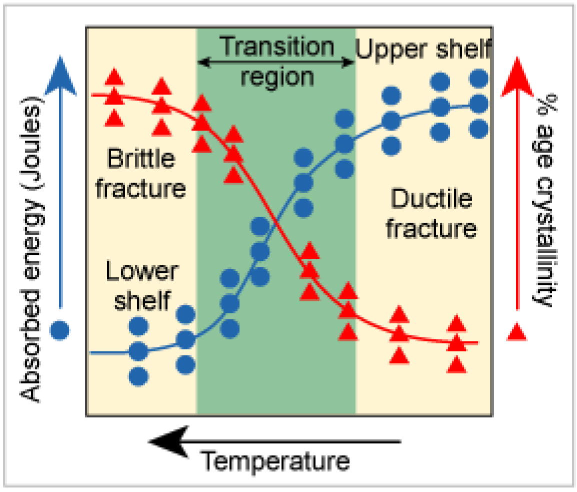



Fig. 3. Schematic Charpy-V energy and % age crystallinity curves

A characteristic of carbon and low alloy steels is that they exhibit a change in fracture behaviour as the temperature falls with the failure mode changing from ductile to brittle.

If impact testing is carried out over a range of temperatures the results of energy absorbed versus temperature can be plotted to give the 'S' curve illustrated in *Fig. 3*.

This shows that the fracture of these types of steels changes from being ductile on the *upper shelf* to brittle on the *lower shelf* as the temperature falls, passing through a *transition* region where the fracture will be mixed.

Many specifications talk of a *transition temperature*, a temperature at which the fracture behaviour changes from ductile to brittle. This temperature is often determined by selecting, quite arbitrarily, the temperature at which the metal achieves an impact value of 27 Joules - see, for example the impact test requirements of EN 10028 Part 2 Steel for Pressure Purposes.

What the curve shows is that a ductile fracture absorbs a greater amount of energy than a brittle fracture *in the same material*. Knowing the temperature at which the fracture behaviour changes is therefore of crucial importance when the service temperature of a structure is considered - ideally in service a structure should operate at upper shelf temperatures.

The shape of the S curve and the positions of the upper and lower shelves are all affected by composition, heat treatment condition, whether or not the steel has been welded, welding heat input, welding consumable and a number of additional factors. All the factors must be controlled if good notch toughness is required. This means that close control of the welding parameters is essential if impact testing is a specification requirement.

Stainless steels, nickel and aluminium alloys do not show this change in fracture behaviour, the fracture remaining ductile even to very low temperatures. This is one reason why these types of alloys are used in cryogenic applications.

In addition to the impact energy there are two further features that can be measured and may be found as a requirement in some specifications. These are *percentage crystallinity* and *lateral expansion*.

The appearance of a fracture surface gives information about the type of fracture that has occurred - a brittle fracture is bright and crystalline, a ductile fracture is dull and fibrous.

Percentage crystallinity is therefore a measure of the amount of brittle fracture, determined by making a judgement of the amount of crystalline or brittle fracture on the surface of the broken specimen.

Lateral expansion is a measure of the ductility of the specimen. When a ductile metal is broken the test piece deforms before breaking, a pair of 'ears' being squeezed out on the side of the compression face of the specimen, as illustrated in *Fig 4*. The amount by which the specimen deforms is measured and expressed as millimetres of lateral expansion. ASME B31.3 for example requires a lateral expansion of 0.38mm for bolting materials and steels with a UTS exceeding 656N/mm $^2$ , rather than specifying an impact value.

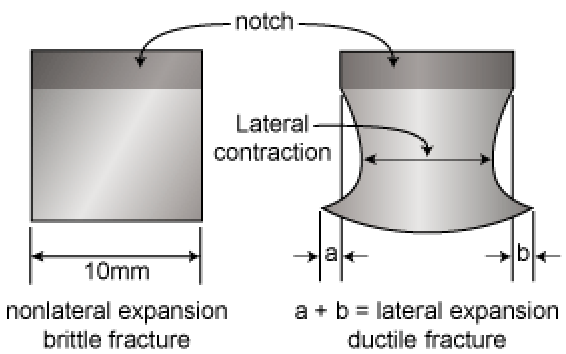



Fig.4 Lateral expansion

The next article in this series will look at the testing of welds, how the impact strength can be affected by composition and microstructure and some of its limitations and disadvantages.

This article was prepared by Gene Mathers.

# Notched bar or impact testing. Part II

The previous article looked at the method of Charpy-V impact testing and the results that can be determined from carrying out a test. This next part looks at the impact testing of welds and some of the factors that affect the transition temperature such as composition and microstructure. Within such a short article, however, it will only be possible to talk in the most general of terms.

Welding can have a profound effect on the properties of the parent metal and there may be many options on process selection, welding parameters and consumable choice that will affect impact strength.

Many application standards therefore require impact testing to be carried out on the parent metal, the weld metal and in the heat affected zone as illustrated in *Fig. 1* which is taken from BS PD 5500 Annex D. The standards generally specify a minimum impact energy to be achieved at the minimum design temperature and to identify from where the specimens are to be taken. This is done in order to quantify the impact energy of the different microstructures in the weld metal and the HAZs to ensure that, as far as possible, the equipment will be operating at upper shelf temperatures where brittle fracture is not a risk.

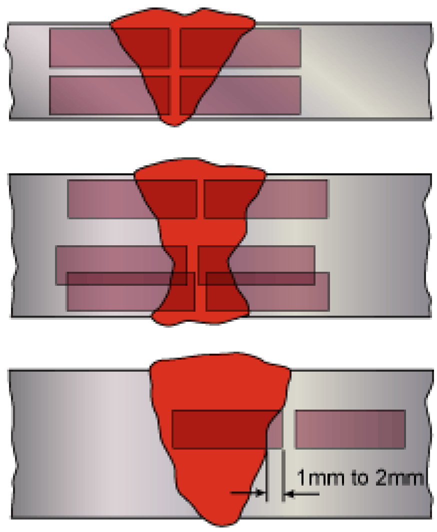



Fig. 1. PD5500 App D. location of Charpy specimens in weld HAZ

These application standards may be supplemented by client specifications that impose additional and more stringent testing requirements, as shown in *Fig. 2* taken from an oil industry specification for offshore structures.

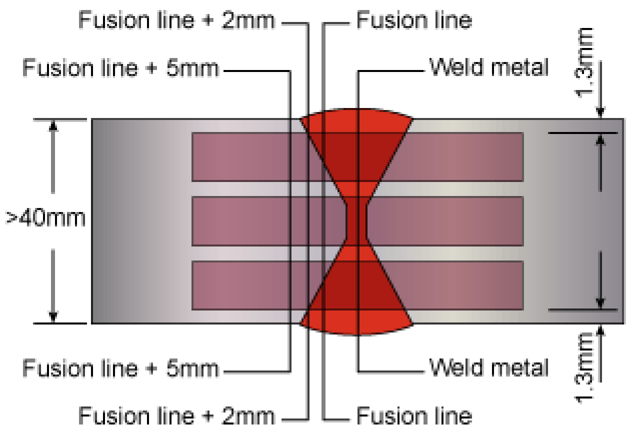



Fig. 2. Offshore client requirements

The positioning of the specimens within a weld is extremely important both in terms of the specimen location and the notch orientation. A specimen positioned across the width of a multi-pass arc weld will probably include more than one weld pass and its associated HAZs. Quite a small movement in the position of the notch can therefore have a significant effect on the impact values recorded during a test. Positioning a notch precisely down the centre line of a single pass of a submerged arc weld can give extremely low impact values!

Testing the heat affected zone also has problems of notch position since in a carbon or low alloy steel there will be a range of microstructures from the fusion line to the unaffected parent metal. Many welds also use a 'V' preparation as illustrated above and this, coupled with the narrow HAZ, means that a single notch may sample all of these structures. If the impact properties of specific areas in the HAZ need to be determined then a 'K' or single bevel preparation may be used.

The standard specimen is 10mm x 10mm square - when a weld joint is thicker than 10mm the machining of a standard size specimen is possible. When the thickness is less than this and impact testing is required it becomes necessary to use sub-size specimens.

Many specifications permit the use of 10mm x 7.5mm, 5mm and 2.5mm thickness (notch length) specimens. There is not a simple relationship between a 10mm x 10mm specimen and the sub-size specimens - a 10mm x 5mm specimen does not have half the notch toughness of the full size test piece. As the thickness decreases the transition temperature also decreases, as does the upper shelf value, illustrated in *Fig. 3* and this is recognised in the application standards.

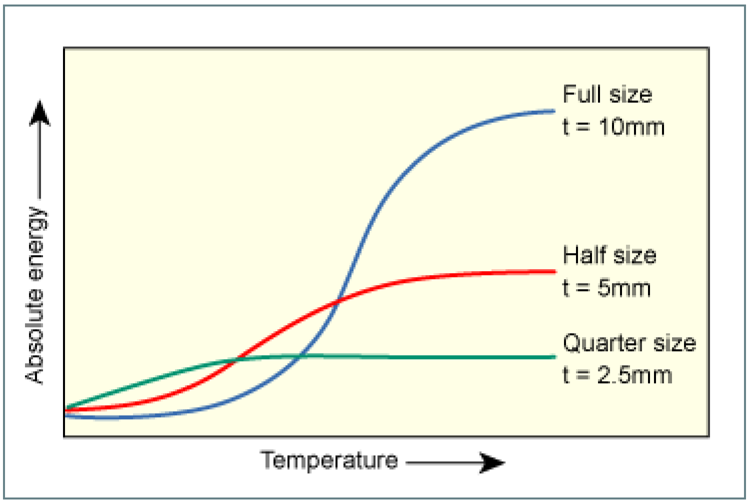



Fig. 3. Effect of size on transition temperature and upper shelf values

In a carbon or low alloy steel the lowest impact values are generally to be found close to the fusion line where grain growth has taken place.

Coarse grains generally have low notch toughness, one reason why heat input needs to be controlled to low levels if high notch toughness is required.

For example, EN ISO 15614 Pt. 1 requires Charpy-V specimens to be taken from the high heat input area of a procedure qualification test piece and places limits on any increase in heat input. Certain steels may also have an area some distance from the fusion line that may be embrittled so some specifications require impact tests at a distance of 5mm from the fusion line.

Charpy-V tests carried out on rolled products show that there is a difference in impact values if the specimens are taken parallel or transverse to the rolling direction. Specimens taken parallel to the rolling direction test the metal across the 'grain' of the steel and have higher notch toughness than the transverse specimens - one reason why pressure vessel plates are rolled into cylinders with the rolling direction oriented in the hoop direction.

In a carbon or low alloy steel the element that causes the largest change in notch toughness is carbon with the transition temperature being raised by around 14° C for every 0.1% increase in carbon content.

An example of how this can affect properties is the root pass of a single sided weld. This often has lower notch toughness than the bulk of the weld as it has a larger amount of parent metal melted into it - most parent metals have higher carbon content than the filler metal and the root pass therefore has a higher carbon content than the bulk of the weld.

Sulphur and phosphorus are two other elements that both reduce notch toughness, one reason why steel producers have been working hard to reduce these elements to as low a level as possible. It is not uncommon for a good quality modern steel to have a sulphur content less than 0.005%.

Of the beneficial elements, manganese and nickel are possibly the two most significant, the nickel alloy steels forming a family of cryogenic steels with the 9% nickel steel being capable of use at temperatures down to -196° C. Aluminium is also beneficial at around 0.02% where it has the optimum effect in providing a fine grain size.

Lastly, let us have a brief look at some of the other factors that can affect the impact values. These are concerned with the quality of the specimen and how the test is conducted.

It goes without saying that the specimens must be accurately machined, the shape of the tip of the notch being the most important feature. A blunted milling cutter or broach will give a rounded notch tip and this in turn will give a false, high impact value. Checking the tip radius on a shadowgraph is one simple way of ensuring the correct tip shape. Correct positioning of the specimen on the anvil is most important and this can be done using a specially designed former.

The last point concerns the testing of specimens at temperatures other than at room temperature. When testing at sub-zero temperatures the length of time taken to remove the specimen from the cooling bath, position it on the anvil and test it is most important. EN875 requires this to be done within five seconds otherwise the test piece temperature will rise making the test invalid - referring back to the impact energy vs temperature curve in the previous article will show why.

## Relevant Specifications

| | | |
|---|---|---|
| BS 131 | Part 4 | Calibration of Impact Testing Machines for metals. |
| BS 131 | Part 5 | Determination of Crystallinity |
| BS 131 | Part 6 | Method for Precision Determination of Charpy-V Impact Energy |
| BS 131 | Part | Specification for Verification of Precision Test Machines |

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| EN 875 | | Destructive Tests on Welds in Metallic Materials - Impact Tests |
| EN 10045 | Part 1 | Test Method |
| EN 10045 | Part 2 | Verification of Impact Testing Machines |
| ASTM E23-02A | | Standard Test Methods for Notched Bar Impact Testing of Metallic Materials. |

This article was written by Gene Mathers.

# Fatigue testing

Fatigue as a specific failure mechanism has been recognised since the early part of the nineteenth century but it was the development of rail travel that resulted in a major increase of interest in this type of fracture.

The premature failure of wagon axles led to Wohler in Germany investigating fatigue failure under rotating loading. This led to the design of the first standardised test - a reversing stress rotating specimen, illustrated in *Fig. 1*.

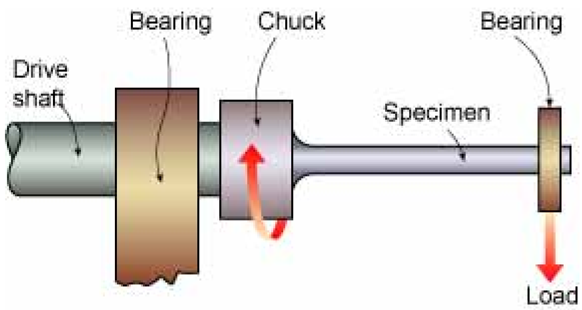
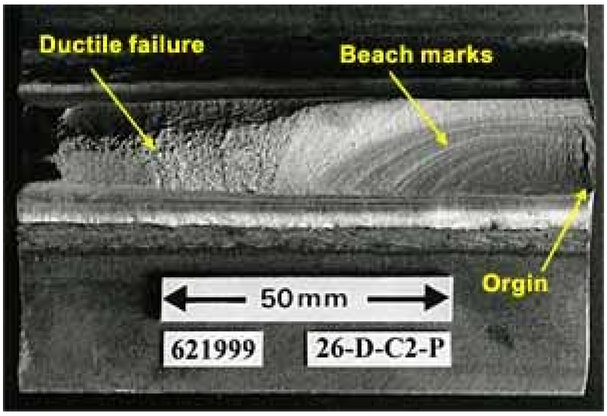



Fig. 1. Wohler rotating fatigue test

There are many mechanisms that can lead to failure but fatigue is perhaps one of the most insidious since it can lead to a catastrophic failure with little or no warning - one well known example being the failure of the Comet aircraft in the 1950s.

Failure can occur at a fluctuating load well below the yield point of the metal and below the allowable static design stress. The number of cycles at which failure occurs may vary from a couple of hundreds to millions. There will be little or no deformation at failure and the fracture has a characteristic surface, as shown in *Fig. 2*.

Fig. 2. Typical fatigue crack fracture surface




The surface is smooth and shows concentric rings, known as beach marks, that radiate from the origin; these beach marks becoming coarser as the crack propagation rate increases. Viewing the surface on a scanning electron microscope at high magnification shows each cycle of stress causes a single ripple. The component finally fails by a ductile or brittle overload.

Fatigue cracks generally start at changes in section or notches where the stress is raised locally and, as a general rule, the sharper the notch the shorter the fatigue life - one reason why cracks are so damaging.

There are two stages in the process of fatigue cracking - a period of time during which a fatigue crack is nucleated and a second stage where the crack grows incrementally leaving the ripples described above. In an unwelded component the bulk of the life is spent in initiating a fatigue crack with a shorter period spent in crack propagation.

An unwelded ferritic steel component exhibits an endurance limit - a stress below which fatigue cracking will not initiate and failure will therefore not occur. This is not the case with most non-ferrous metals or with welded joints - these have no clearly defined endurance limit.

The reason for this is that in arc welded joints there is an 'intrusion' - a small defect at the toe of the weld, perhaps only some 0.1mm deep. Provided that the applied stress is sufficiently large a crack will begin to propagate within an extremely short period of time. The endurance limit for a welded joint is therefore dependent on the intrusion size that does not result in crack propagation at the applied stress range. In the case of a welded joint, therefore, a fatigue limit - a 'safe life' is specified, often the stress to cause failure at $2x10^{6}$ or $10^{7}$ cycles.

During fatigue the stress may alternate about zero, may vary from zero to a maximum or may vary about some value above - or below - zero.

To quantify the effect of these varying stresses fatigue testing is carried out by applying a particular stress range and this is continued until the test piece fails. The number of cycles to failure is recorded and the test then repeated at a variety of different stress ranges.

This enables an S/N curve, a graph of the applied stress range, S, against N, the number of cycles to failure, to be plotted as illustrated in *Fig. 3*. This graph shows the results of testing a plain specimen and a welded component. The endurance limit of the plain specimen is shown as the horizontal line - if the stress is below this line the test piece will last for an infinite number of cycles. The curve for the welded sample, however, continues to trend down to a point where the stress range is insufficient to cause a crack to propagate from the intrusion.

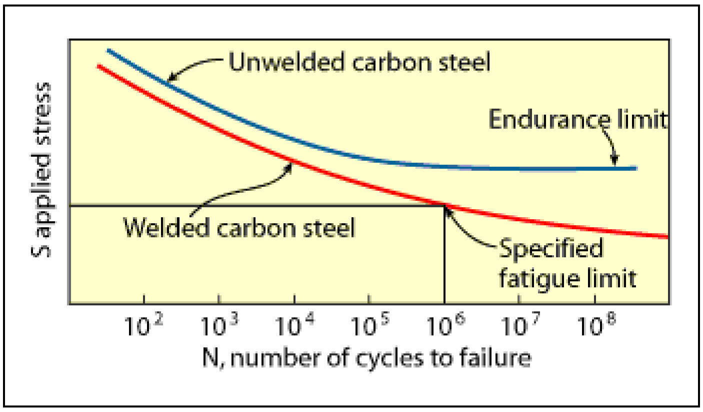



Fig. 3. S/N curves for welded and unwelded specimens

By testing a series of identical specimens it is possible to develop S/N curves. In service however, there will be variations in stress range and frequency. The direction of the load may vary, the environment and the shape of the component will all affect the fatigue life, as explained later in this article.

When designing a test to determine service performance it is therefore necessary to simulate as closely as possible these conditions if an accurate life is to be determined. In order to enable the fatigue life to be calculated when the stress range varies in this random manner, the Palmgren-Miners cumulative damage rule is used.

This rule states that, if the life at a given stress is N and the number of cycles that the component has experienced is a smaller number, n, then the fatigue life that has been used up is n/N.

If the number of cycles at the various stress ranges are then added together - $n_1/N_1 + n_2/N_2 + n_3/N_3 + n_4/N_4$ etc - the fatigue life is used up when the sum is of all these ratios is 1. Although this does not give a precise estimate of fatigue life, Miners rule was generally regarded as being safe. This method, however, has now been superceded with the far more accurate approach detailed in the British Standard BS 7608.

The design of a welded joint has a dominant effect on fatigue life. It is therefore necessary to ensure that a structure that will experience fatigue loading in the individual joints has adequate strength. The commonest method for determining fatigue life is to refer to S/N curves that have been produced for the relevant weld designs.

The design rules for this range of joint designs were first developed by TWI and incorporated with the bridge code BS 5400 in 1980 and then into the industry design rules for offshore structures. Further refinements and improvements finally resulted in the publication of BS 7608 Code of practice for fatigue design and assessment of steel structures. This standard will be looked at in more detail in a future article.

This article was written by Gene Mathers.

# Fatigue testing - Part 2

The article in the September/October issue of *Connect* established some basic facts about fatigue and the statement was made that a welded joint exhibited no clearly established fatigue limit as in an unwelded component. In this article we will be looking at some of the reasons for this behaviour.

It should be mentioned that, in service, few structures experience purely static loads and that most will be subjected to some fluctuations in applied stresses and may therefore be regarded as being fatigue loaded. Motorway gantries, for example, are buffeted by the slipstream from large lorries and offshore oilrigs by wave action. Process pressure vessels will experience pressure fluctuations and may also be thermally cycled.

If these loads are not accounted for in the design, fatigue failure may occur in as few as a couple of tens of cycles or several million and the result may be catastrophic when it does.

Fatigue failures can occur in both welded and unwelded components, the failure usually initiating at any changes in cross section - a machined groove, a ring machined onto a bar or at a weld. The sharper the notch the greater will be its effect on fatigue life.

The effect of a change in section is illustrated in *Fig. 1*, where it can be seen that the stress is locally raised at the weld toe. The illustration shows a bead-on-plate run but a full penetration weld will show the same behaviour.

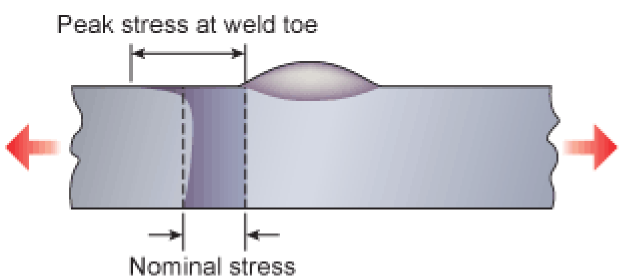



Fig. 1. Stress concentrating effect of a change in thickness

In addition, misalignment and/or distortion of the joint will cause the applied stress to be further increased, perhaps by introducing bending in the component, further reducing the expected fatigue life. A poorly shaped weld cap with a sharp transition between the weld and the parent metal will also have an adverse effect on fatigue performance.

In addition to these geometrical features affecting fatigue life there is also the small intrusion at the weld toe, mentioned in the last article and illustrated in *Fig. 2*. In an unwelded component the bulk of the fatigue life is spent in initiating the fatigue crack with a smaller proportion spent in the crack propagating through the structure. In a welded component the bulk of the fatigue life is spent in propagating a crack. The consequences of this difference in behaviour are illustrated in *Fig. 3*.

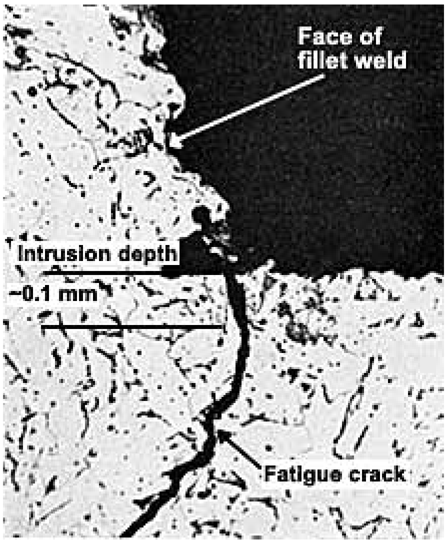



Fig. 2. Weld toe intrusion

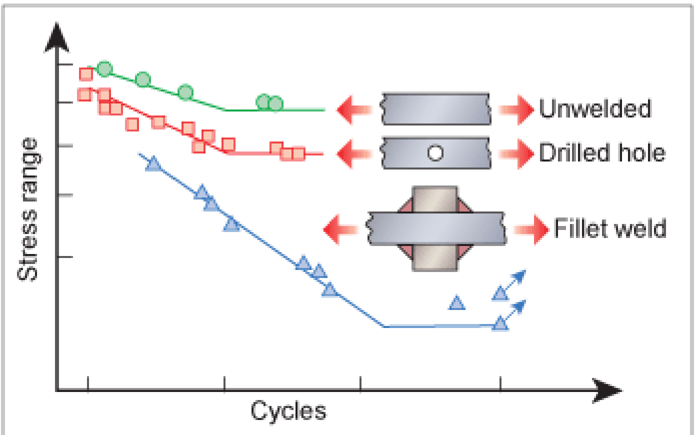



Fig. 3. Effect of stress concentration on fatigue life

This shows that this small intrusion reduces the fatigue life of a fillet welded joint by a factor of perhaps 10 compared with that of an unwelded item and some eight times that of a sample with a machined hole. The other consequence is that fatigue cracks in welded joints almost always initiate at the toe of a weld, either face or root.

It may be thought that the use of a higher strength material will be of benefit in increasing fatigue life. The rate of crack propagation, however, is determined by Young's Modulus - a measure of the elastic behaviour of the metal - and not simply by tensile strength.

Alloying or heat treatment to increase the strength of a metal has very little effect on Young's Modulus and therefore very little effect on crack propagation rates. Since the bulk of a welded component's life is spent in propagating a crack, strength has little or no influence on the fatigue life of a welded item. There is thus no benefit to be gained by using high strength alloys if the design is fatigue limited. This is illustrated in *Fig. 4* which shows the benefits of increasing the ultimate tensile strength of a steel if the component is unwelded or only machined but how little effect this has on the life of a welded item.

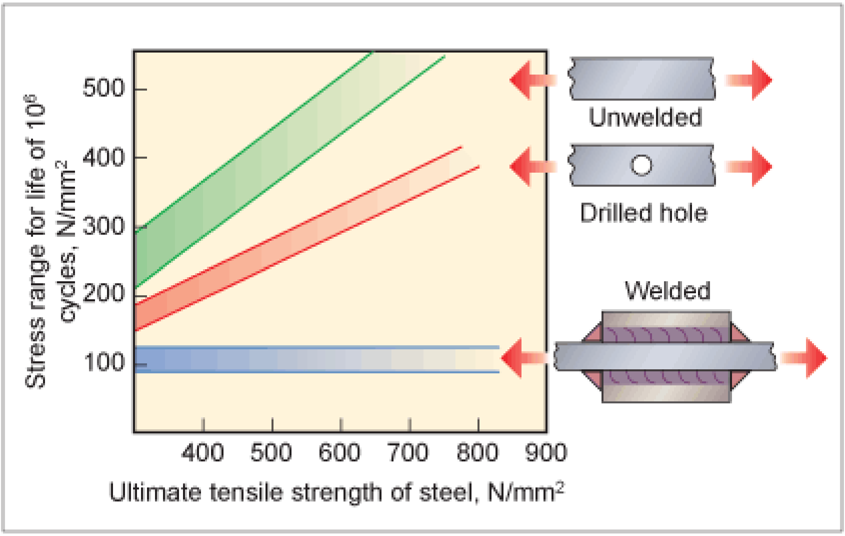



Fig. 4. Effect of increase in tensile strength on fatigue life

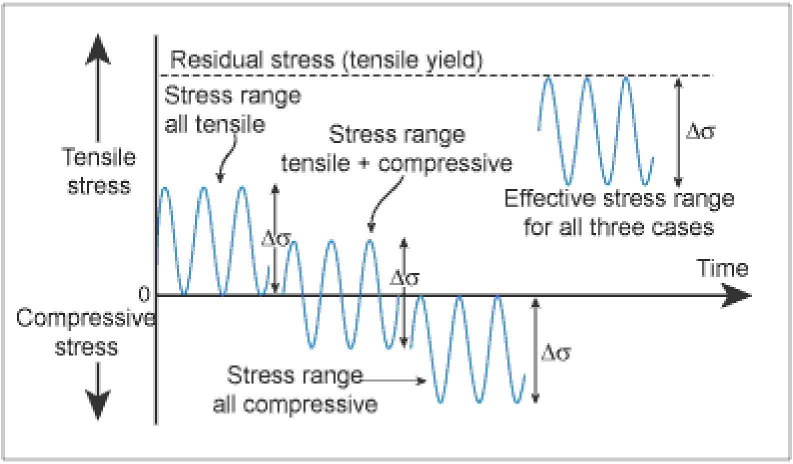
One additional feature in welded joints that set them apart from unwelded or machined items is the presence of residual tensile stress.

In a welded component there will be stresses introduced into the structure by, for example, assembly stress. These stresses are long range reaction stresses and from a fatigue point of view have little effect on fatigue life.

Of far greater significance with respect to fatigue are the short range stresses introduced into the structure by the expansion and contraction of material close to and within the welded joint. Whilst the actual level of residual stress will be affected by such factors as tensile strength, joint type and size and by run size and sequence, the peak residual stress may be regarded as being of yield point magnitude. The implications of this are that it is the stress range that determines fatigue life and not the magnitude of the nominal applied stress.

Even if the applied stress range is wholly compressive and there is apparently no fluctuating tensile stress to cause a crack to form and grow, the effect of welding residual stress is to make the structure susceptible to fatigue failure. This is illustrated in *Fig. 5*, where it can be seen that, irrespective of the applied stress, the effective stress range is up to the level of residual stress at the welded joint.

Fig. 5. Effect of residual stress on stress range




It would seem reasonable, therefore, that a post-weld stress relief treatment would be of benefit to the fatigue life by reducing the residual stresses to low levels. This is only true, however, where the applied stress range is partly or wholly compressive. If the applied stress range is all tensile, research has shown that as-welded and stress relieved components have almost identical fatigue performances with only a marginal improvement in the stress relieved joints.

This is the result of the bulk of the fatigue life of a welded joint being spent in crack propagation where propagation rates are only marginally affected by mean stress. It may be difficult therefore to justify the cost of stress relief if the only criterion is that of improving fatigue life.

The methods of determining fatigue performance of welded joints, as detailed in BS 7608, and how fatigue performance can be improved will be dealt with in the next *Connect* article.

This article was written by Gene Mathers.

# Fatigue testing Part 3

What will have become obvious from the previous two articles on fatigue is that a welded joint behaves in a radically different way from an unwelded item, even if this item contains a significant stress raiser.

The last article, number 79, made the statement that a welded joint exhibits no clearly defined fatigue limit, the limit varying dependent upon the joint type and weld quality. It is vitally important to understand this if fatigue analysis of welded joints is to be carried out.

As mentioned earlier, rules for the design of components subject to fatigue loading were produced by TWI and these were incorporated into the design rules in BS 5400, the British bridge design code. These rules were later adopted by the offshore industry for offshore structures and adaptations of these rules now appear in many other specifications such as BS PD 5500 Unfired pressure vessels and BS 8118 Structural use of aluminium.

The basis of all the rules is a system whereby various joint designs are assigned a 'classification' related to the joint's fatigue performance. *Fig. 1* is an example of how this classification has been formalised in BS 7608 - the same or similar methods will be found in other application standards.

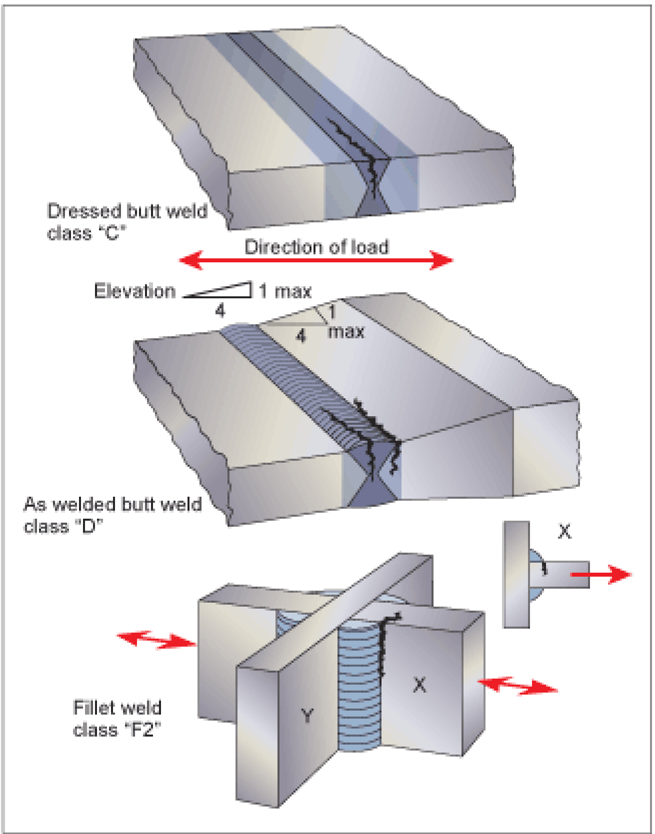
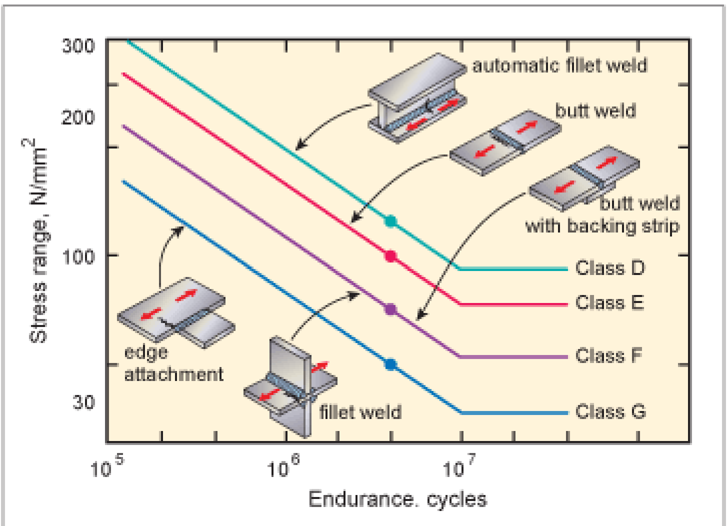



Fig. 1. Examples of joint classification from BS 7608

In BS 7608 each joint type is assigned a classification letter. For example, a plate butt weld with cap and root ground flush is class 'C', an undressed plate butt weld class 'D' and a fillet weld class 'F' ( *Fig. 2*).

Fig. 2. Effects of joint classification on fatigue life




For each classification a fatigue curve has been developed and from these curves the design life can be predicted. This is obviously an over-simplification of what can be a very complicated task -the forces acting on a joint arising from changes in temperature, changes in internal or external pressure, vibration, externally applied fluctuating loads etc can be complex and difficult to determine.

Whilst the joint design has a major effect on design life and is the basis for calculating service performance, the weld quality also has a decisive effect - any fatigue analysis assumes that the welds are of an acceptable quality and comply with the inspection acceptance standards. However, in practice it is not always possible to guarantee a 'perfect' weld and cracks, lack of fusion, slag entrapment and other planar defects may be present, reducing the fatigue life, perhaps catastrophically.

Other less obvious features will also have an adverse effect. Excessive cap height or a poorly shaped weld bead will raise the stress locally and reduce the design life; misalignment may cause local bending with a similar effect. Good welding practices, adherence to approved procedures and competent and experienced staff will all help in mitigating these problems.

In some applications an as-welded joint will not have a sufficient design life and some method of improving the fatigue performance needs to be found. There are a number of options available. The first and perhaps simplest is to move the weld from the area of highest stress range, the next is to thicken up the component or increase the weld size. Note that, as mentioned in the earlier article, using a higher strength alloy will not improve the fatigue life.

Local spot heating to induce compressive stresses at the weld toes will also help, although this needs very accurate positioning of the heated area and very careful control of the temperature if an improvement is to be seen and the strength of the metal is not to be affected. For these reasons, spot heating for fatigue improvements has been virtually discontinued.

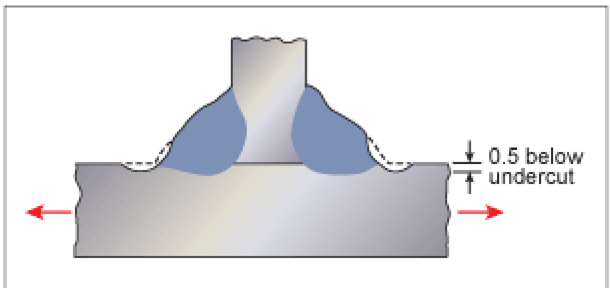
Hammer peening with a round nosed tool or needle gun peening gives very good results although the noise produced may prevent their use. Shot peening can also be used to introduce compressive stresses at weld toes with equally good results. Compressive stresses can be induced in a component by overstressing - a pressure test of a pressure vessel is a good example of this - where local plastic deformation at stress raisers induces a compressive stress when the load is released. This technique needs to be approached with some care as it may cause permanent deformation and/or any defects to extend in an unstable manner resulting in failure.

Although the next techniques described are not as beneficial as hammer peening of the weld toes they have the advantage of being more consistent and easier to control. The techniques rely upon dressing the weld toes to improve the shape and remove the intrusion mentioned in article 79. The dressing may be carried out using a TIG or plasma-TIG torch which melts the region of the weld toe, providing a smooth blend between the weld face and the parent metal.

Alternatively the toe may be dressed by the careful use of a disc grinder but for best results the toe should be machined with a fine rotary burr as shown in *Fig. 3* and *4*. Great care needs to be exercised to ensure that the operator does not remove too much metal and reduce the component below its minimum design thickness and that the machining marks are parallel to the axis of the main stress. Ideally the dressing should remove no more than 0.5m depth of material, sufficient to give a smooth blend and remove the toe intrusion. The results of these improvement techniques are summarised in *Fig. 5*.

Fig. 3. Grinding tools

Fig. 4. Burr machining of weld toes



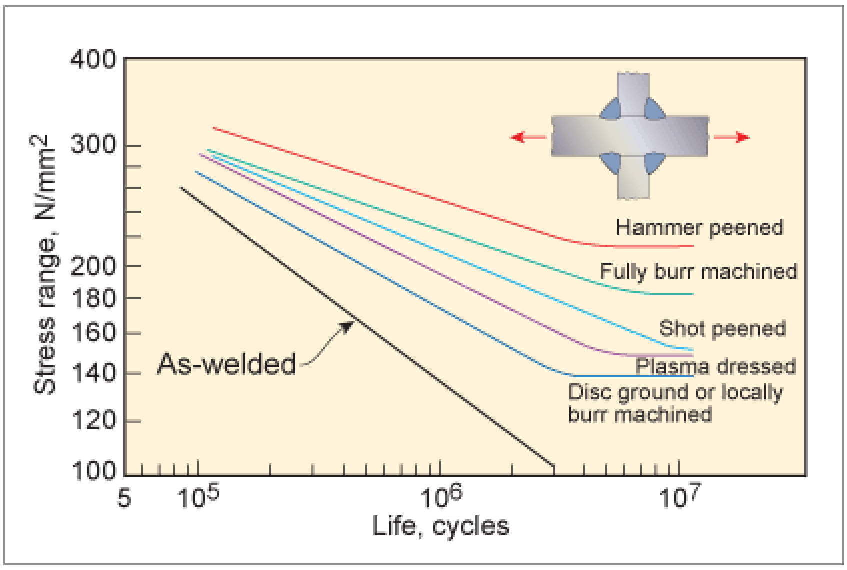




Fig. 5. Improvement in fillet weld fatigue life

Whilst fatigue has resulted in some catastrophic and unexpected failures, the improvements in design life calculation methods, particularly the use of powerful software packages allowing detailed finite element analyses to be performed, has enabled engineers to approach the design of fatigue limited structures with far more confidence. This still means, however, that the designer has to recognise the effect of welds in the structure and must consider all possible sources of loading and ALL welds, even non-load carrying attachments that may be thought to be unimportant to service performance.

This article was written by Gene Mathers.

# Creep and creep testing

The use of metals at high temperatures introduces the possibility of failure in service by a mechanism known as creep.

As the name suggests this is a slow failure mechanism that may occur in a material exposed for a protracted length of time to a load below its elastic limit (see Connect article No. 69), the material increasing in length in the direction of the applied stress. At ambient temperature with most materials this deformation is so slow that it is not significant, although the effect of low temperature creep can be seen in the lead on church roofs and in mediaeval glazing, where both materials have slumped under the force of gravity.

For most purposes such movements are of little or no importance. Increasing the temperature, however, increases the rate of deformation at the applied load and it is vitally important to know the speed of deformation at a given load and temperature if components are to be safely designed for high temperature service. Failure to be able to do this may result in, for example, the premature failure of a pressure vessel or the fouling of gas turbine blades on the turbine casing.

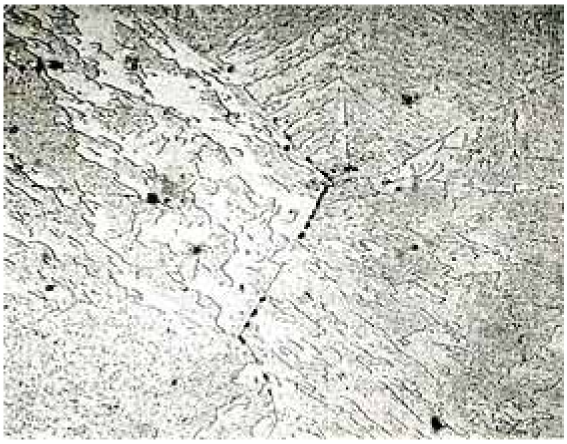
The drive for the more efficient use of fuels in applications such as power generation plant and gas turbines demands that components are designed for higher and higher operating temperatures, requiring new creep resistant alloys to be developed. To investigate these alloys and to produce the design data the creep test is used.

In metals, creep failure occurs at the grain boundaries to give an intergranular fracture. *Fig. 1* illustrates the voids that form on the grain boundaries in the early stages of creep. The fracture appearance can be somewhat similar to a brittle fracture, with little deformation visible apart from a small amount of elongation in the direction of the applied stress.

Fig. 1. The voids that form on the grain boundaries in the early stages of creep

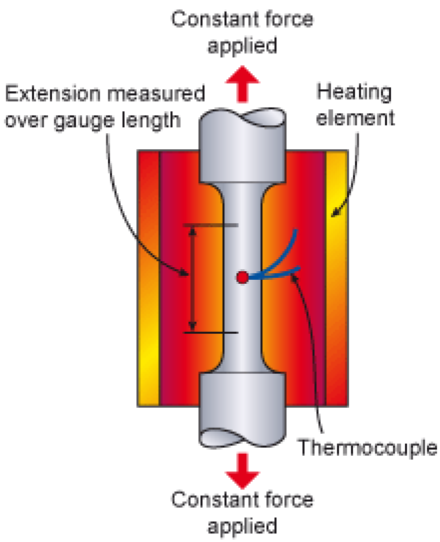
a)

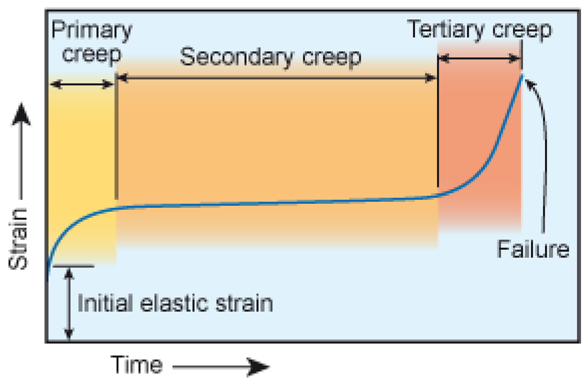
b)



The creep test is conducted using a tensile specimen to which a constant stress is applied, often by the simple method of suspending weights from it. Surrounding the specimen is a thermostatically controlled furnace, the temperature being controlled by a thermocouple attached to the gauge length of the specimen, *Fig. 2*. The extension of the specimen is measured by a very sensitive extensometer since the actual amount of deformation before failure may be only two or three per cent. The results of the test are then plotted on a graph of strain versus time to give a curve similar to that illustrated in *Fig. 3*.

Fig. 2. Schematic of a creep test Fig. 3. Typical creep curve for steel




The test specimen design is based on a standard tensile specimen. It must be proportional (see Connect Article No. 69) in order that results can be compared and ideally should be machined to tighter tolerances than a standard tensile test piece. In particular the straightness of the specimen should be controlled to within some ½% of the diameter. A slightly bent specimen will introduce bending stresses that will seriously affect the results. The surface finish is also important - the specimen should be smooth, scratch free and not cold worked by the machining operation. The extensometer should be fitted on the gauge length and not to any of the other load carrying parts as it is difficult to separate any extension of these parts from that in the specimen.

Testing is generally carried out in air at atmospheric pressure. However, if it is necessary to produce creep data for materials that react with air these may be tested in a chamber containing an inert atmosphere such as argon or in a vacuum. If the material is to operate in an aggressive environment then the testing may need to be carried out in a controlled environment simulating service conditions.

*Fig. 3* shows that creep failure occurs in three distinct phases - a rapid increase in length known as primary creep where the creep rate decreases as the metal work hardens. This is followed by a period of almost constant creep rate, steady state or secondary creep and it is this period that forms the bulk of the creep life of a component. The third stage, tertiary creep, occurs when the creep life is almost exhausted, voids have formed in the material and the effective cross sectional area has been reduced. The creep rate accelerates as the stress per unit area increases until the specimen finally fails. A typical failed specimen is illustrated in *Fig. 4*.


Fig. 4. Fractured test specimen

The creep test has the objective of precisely measuring the rate at which secondary or steady state creep occurs. Increasing the stress or temperature has the effect of increasing the slope of the line ie the amount of deformation in a given time increases. The results are presented as the amount of strain (deformation), generally expressed as a percentage, produced by applying a specified load for a specified time and temperature eg 1% strain in 100,000hrs at 35N/mm $^2$ and 475° C.

This enables the designer to calculate how the component will change in shape during service and hence to specify its design creep life. This is of particular importance where dimensional control is crucial, in a gas turbine for instance, but of less importance where changes in shape do not significantly affect the operation of the component, perhaps a pressure vessel suspended from the top and which can expand downwards without being compromised.

There are therefore two additional variations on the creep test that use the same equipment and test specimen as the standard creep test and that are used to provide data for use by the designer in the latter case. These are the creep rupture test and the stress rupture test. As the names suggest both of these tests are continued until the specimen fails. In the creep rupture test the amount of creep that has occurred at the point of failure is recorded. The test results would be expressed as %age strain, time and temperature eg rupture occurs at 2% strain at 450° C in 85,000 hours. The stress rupture test gives the time to rupture at a given stress and temperature eg 45N/mm $^2$ will cause failure at 450° C in 97,000 hrs. This data, if properly interpreted, is useful in specifying the design life of components when dimensional changes due to creep are not important since they give a measure of the load carrying capacity of a material as a function of time.

| Relevant Specifications | |
|---|---|
| BS EN 10291 | Metallic Materials - Uniaxial Creep Testing in Tension. |
| BS 3500 | Methods for Creep and Rupture testing of Metals. |
| ASTM E139 | Conducting Creep, Creep Rupture and Stress Rupture Tests of Metallic Materials. |
| BS EN ISO 899 | Plastics - Determination of Creep Behaviour. |
| BS EN 761 | Creep Factor Determination of Glass - Reinforced Thermosetting Plastics - Dry Conditions. |
| BS EN 1225 | Creep Factor Determination of Glass - Reinforced Thermosetting Plastics - Wet Conditions. |

This article was written by Gene Mathers.

# Hardness Testing Part 1

The hardness of a material can have a number of meanings depending upon the context, which in the case of metals generally means the resistance to indentation. There are a number of test methods of which only the Brinell, Vickers and portable hardness testing will be covered in this article.

## Brinell Hardness Test

The Brinell test was devised by a Swedish researcher at the beginning of the 20th century. The test comprises forcing a hardened steel ball indentor into the surface of the sample using a standard load as shown in *Fig.1(a)*. The diameter/load ratio is selected to provide an impression of an acceptable diameter. The ball may be 10, 5 or 1mm in diameter, the load may be 3000, 750 or 30kgf, The load, P, is related to the diameter, D by the relationship $P/D^2$ and this ratio has been standardised for different metals in order that test results are accurate and reproducible. For steel the ratio is 30:1 - for example a 10mm ball can be used with a 3000kgf load or a 1mm ball with a 30kgf load. For aluminium alloys the ratio is 5:1. The load is applied for a fixed length of time, usually 30 seconds. When the indentor is retracted two diameters of the impression, $d_1$ and $d_2$, are measured using a microscope with a calibrated graticule.and then averaged as shown in *Fig.1(b)*.

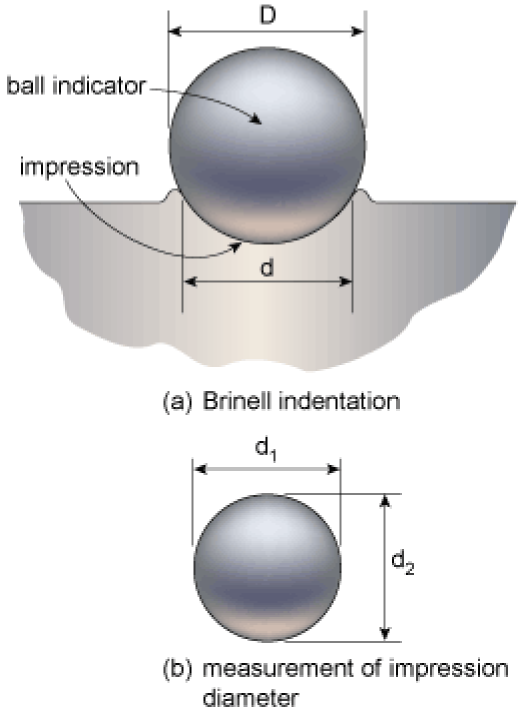



Fig.1. Brinell Hardness Test

The Brinell hardness number (BHN) is found by dividing the load by the surface area of the impression. There is a somewhat tedious calculation that can be carried out to determine the hardness number but it is more usual and far simpler to refer to a set of standard tables from which the Brinell hardness number can be read directly.

The Brinell test is generally used for bulk metal hardness measurements - the impression is larger than that of the Vickers test and this is useful as it averages out any local heterogeneity and is affected less by surface roughness. However, because of the large ball diameter the test cannot be used to determine the hardness variations in a welded joint for which the Vickers test is preferred. Very hard metals, over 450BHN may also cause the ball to deform resulting in an inaccurate reading. To overcome this limitation a tungsten carbide ball is used instead of the hardened steel ball but there is also a hardness limit of 600BHN with this indentor.

# Vickers Hardness Test

The Vickers hardness test operates on similar principles to the Brinell test, the major difference being the use of a square based pyramidal diamond indentor rather than a hardened steel ball. Also, unlike the Brinell test, the depth of the impression does not affect the accuracy of the reading so the $P/D^2$ ratio is not important. The diamond does not deform at high loads so the results on very hard materials are more reliable. The load may range from 1 to 120kgf and is applied for between 10 and 15 seconds.

The basic principles of operation of the Vickers hardness test are illustrated in *Fig.2* where it can be seen that the load is applied to the indentor by a simple weighted lever. In older machines an an oil filled dash pot is used as a timing mechanism - on more modern equipment this is done electronically.

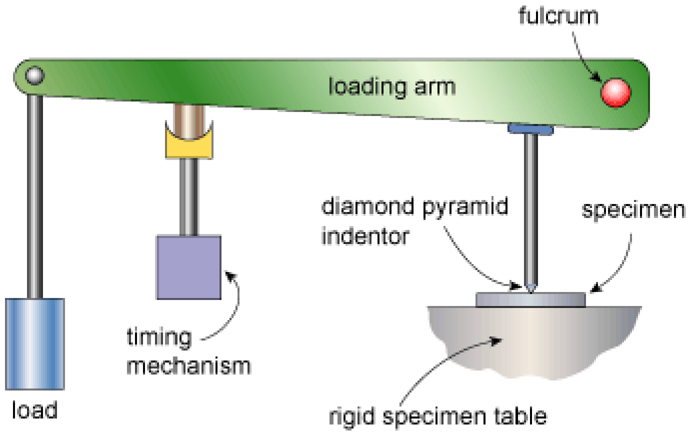



Fig. 2. Schematic principles of operation of Vickers hardness machine

As illustrated in *Fig. 3(b)* two diagonals, $d_1$ and $d_2$, are measured, averaged and the surface area calculated then divided into the load applied. As with the Brinell test the diagonal measurement is converted to a hardness figure by referring to a set of tables. The hardness may be reported as Vickers Hardness number (VHN), Diamond Pyramid Number (DPN) or, most commonly, $Hv_{xx}$ where 'xx' represents the load used during the test.

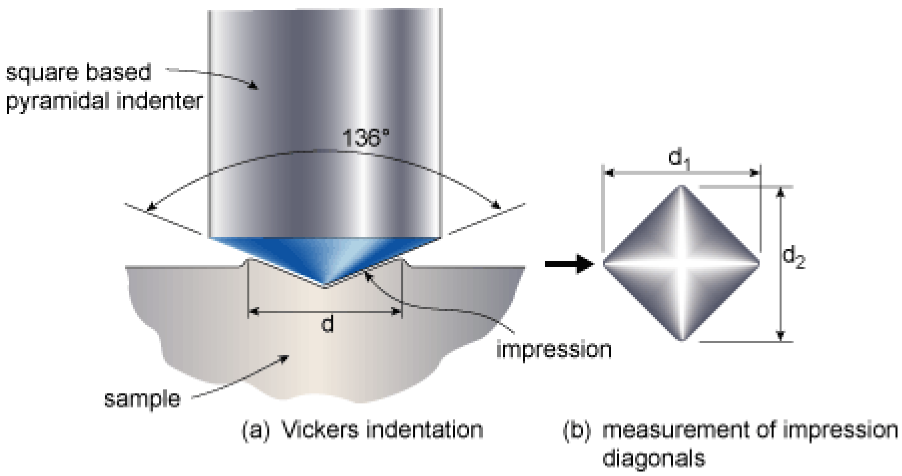



Fig. 3. Vickers hardness test

As mentioned earlier, the Vickers indentation is smaller than the Brinell impression and thus far smaller areas can be tested, making it possible to carry out a survey across a welded joint, including individual runs and the heat affected zones. The small impression also means that the surface must be flat and perpendicular to the indentor and should have a better than 300 grit finish.

# Errors in Hardness Testing

There are many factors that can affect the accuracy of the hardness test. Some of these such as flatness and surface finish have already been mentioned above but it is worth re-emphasising the point that flatness is most important - a maximum angle of approximately ± 1° would be regarded as acceptable.

To achieve the required flatness tolerance and surface finish surface grinding or machining may be necessary. The correct load must be applied and to

achieve this there must be no friction in the loading
system otherwise the impression will be smaller than expected - regular maintenance and calibration of the machine is therefore essential. The condition of the indentor is crucial - whilst the Vickers diamond is unlikely to deteriorate with use unless it is damaged or loosened in its mounting by clumsy handling, the Brinell ball will deform over a period of time and inaccurate readings will result. This deterioration will be accelerated if a large proportion of the work is on hard materials. The length of time that the load is applied is important and must be controlled.

The specimen dimensions are important - if the test piece is too thin the hardness of the specimen table will affect the result. As a rule of thumb the specimen thickness should be ten times the depth of the impression for the Brinell test and twice that of the Vickers diagonal. Similarly, if the impression is too close to the specimen edge then low hardness values will be recorded - again as a rule the impression should be some 4 to 5 times the impression diameter from any free edge. Performing hardness testing on cylindrical surfaces eg pipes and tubes, the radius of curvature will affect the indentation shape and can lead to errors. It may be necessary to apply a correction factor - this is covered in an ISO specification, ISO 6507 Part 1.

The specimen table should be rigidly supported and must be in good condition - burrs or raised edges beneath the sample will give low readings. Impact loading must be avoided. It is very easy to force the indentor into the specimen surface when raising the table into position. This can strain the equipment and damage the indentor. Operator training is crucial and regular validation or calibration is essential if hardness rest results are to be accurate and reproducible.

This article was written by Gene Mathers.

# Hardness Testing Part 2

The previous article dealt with the conventional Vickers and Brinell hardness tests. This second article reviews micro-hardness and portable hardness testing. The investigation of metallurgical problems in welds often requires the determination of hardness within a very small area or on components in service or too large to be able to test in a laboratory environment.

Micro-hardness testing may be carried out using any one of three common methods and, as with the macro-hardness tests, measure the size of the impression produced by forcing an indentor into the specimen surface under a dead load, although many of the new test machines use a load cell system.

The three most common tests are the Knoop test, the Vickers test and the ultrasonic micro-hardness test.

The Knoop test uses a pyramidal indentor that gives an elongated diamond shaped impression with an aspect ratio of around 7:1, the Vickers test uses the pyramidal indentor described in the previous article (January/February 2005).

The Knoop test is rarely used in Europe where the Vickers test is the preferred method. The loads used for the tests vary from 1gmf to 1kgf and produce impressions that need to be measured by using a microscope with magnifications of up to 100X, although modern machines may be equipped with an image analysis system that enables the process to be automated.

The ultrasonic hardness test does not rely upon measuring the size of an impression. Instead, the test uses a Vickers diamond attached to the end of a metal rod. The rod is vibrated at its natural frequency by a piezoelectric converter and then brought into contact with the specimen surface under a small load. The resonant frequency is changed by the size of the impression produced and this change can be measured and converted to a hardness value.

The size of the impression is extremely small and the test may be regarded as non-destructive since it is non-damaging in most applications.

The micro-hardness test has a number of applications varying from being a metallurgical research tool to a method of quality control. The test may be used to determine the hardness of different micro-constituents in a metal, as shown in *Fig.1*. Where an impression would be damaging, for instance on a finished product, micro-hardness tests, particularly the ultrasonic test, may be used for quality control purposes. Micro-hardness testing also finds application in the testing of thin foils, case hardened items and decarburised components.

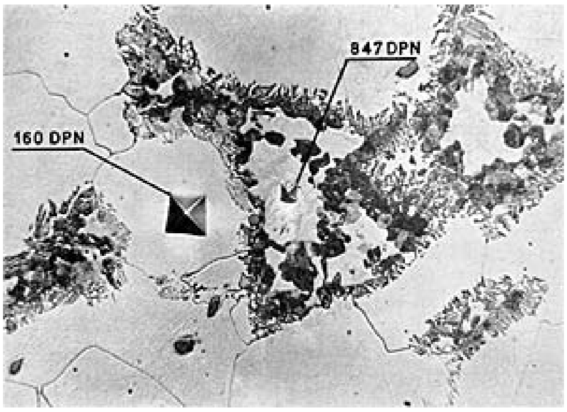



Fig.1. Micro-hardness test

Portable hardness tests may be used where the component is too large to be taken to the testing machine or in on-site applications. It is useful on-site, for example, for checking that the correct heat treatment has been carried out on welded items or that welded joints comply with the hardness limits specified by NACE for sour service. There are three principal methods - dynamic rebound, Brinell or Vickers indentation or ultrasonic testing.

The Leeb hardness test uses dynamic rebound where a hammer is propelled into the test piece surface and the height of the rebound is measured. This gives a measure of the elasticity of the material and hence its hardness.

This type of test is typified by the 'Equotip' test, *Fig.2*, a trademark of Proceq SA. The Equotip tester comprises a hand-held tube that contains a spring loaded hammer. The device is cocked by compressing the hammer against the spring, the device is then positioned vertically on the test surface and the release button is pressed. The hammer strikes the surface, rebounds and the result displayed digitally. Generally the average of five readings is taken.


Fig. 2. Equotip test

To obtain a valid result, the position of the device, the flatness of the surface and the flexibility of the component all affect the accuracy of the results. Needless to say the skill and experience of the operator is one of the key factors in producing accurate hardness figures. The results are generally converted to give a hardness in Vickers or Brinell units.

The other type of portable hardness test in common use is the ultrasonic method described above. Commercially available machines are typified by the Microdur unit supplied by GE Inspection Technologies as shown in *Fig. 3*. This type of equipment is electronically based and can be programmed to give hardness readings of any type - Vickers, Brinell, or Rockwell. Needless to say, any of these methods of hardness testing require regular calibration of the equipment, fully trained operators and well prepared surfaces.

Fig. 3. Ultrasonic testing using a Microdur unit

Although there are several different methods of hardness testing the results can be compared and converted. The ASTM specification E140 contains conversion tables for metals - ferritic and austenitic steels, nickel alloys, copper and brass- for converting Vickers to Brinell or Rockwell or vice versa.

To end this article on hardness testing let us look at the significance of the results.

Hardness is related to tensile strength - multiplying the Vickers hardness number of a carbon steel by 3.3 will give the approximate ultimate tensile strength in N/mm $^2$. A hardness traverse across a weld and its HAZs will therefore reveal how the tensile strength varies, as illustrated in *Fig. 4* which is for a work hardened aluminium alloy. In carbon or low alloy steels a hardness of above approximately 380HV suggests that the hard brittle microstructure, martensite, has been formed leading to the possibility of cold cracking during fabrication or brittle fracture in service. This fact has been recognised in the specification EN ISO 15614 Part 1 so that a maximum hardness of 380HV is permitted on a hardness traverse of a macro-section from a carbon steel procedure qualification test.

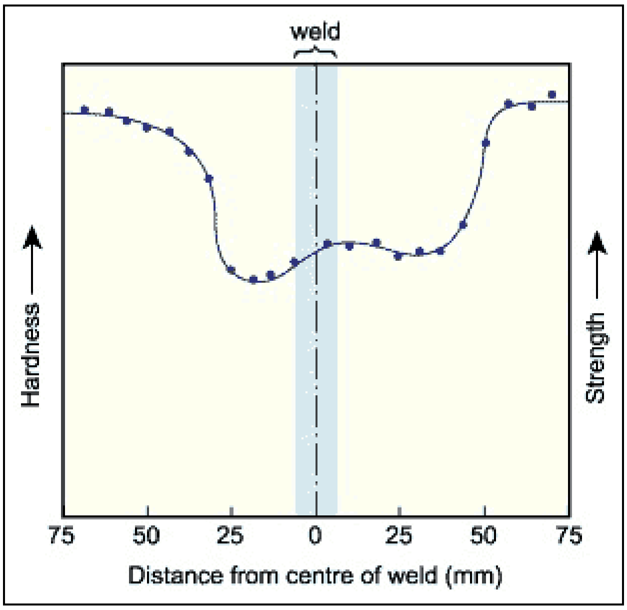



Fig. 4. Variation in tensile strength across a weld

Relevant Specifications.
ASTM E 10 Brinell Hardness of Metallic Materials
ASTM E 140 Hardness Conversion Tables for Metals.
ASTM E 110 Portable Hardness Testing.
ASTM E 384 Microhardness Testing of Metallic Materials.

ASTM E 103 Rapid Indentation Hardness Testing.
ASTM E 18 Rockwell Hardness Testing.
ASTM E 92 Vickers Hardness of Metallic Materials.

This article was written by Gene Mathers.

# Bend testing

The bend test is a simple and inexpensive qualitative test that can be used to evaluate both the ductility and soundness of a material. It is often used as a quality control test for butt-welded joints, having the advantage of simplicity of both test piece and equipment.

No expensive test equipment is needed, test specimens are easily prepared and the test can, if required, be carried out on the shop floor as a quality control test to ensure consistency in production.

The bend test uses a coupon that is bent in three point bending to a specified angle.

The outside of the bend is extensively plastically deformed so that any defects in, or embrittlement of, the material will be revealed by the premature failure of the coupon.

The bend test may be free formed or guided.

The guided bend test is where the coupon is wrapped around a former of a specified diameter and is the type of test specified in the welding procedure and welder qualification specifications. For example, it is a requirement in ASME IX, the EN 287 and EN 288 series of specifications and ISO 15614 Part 1.

As the guided bend test is the only form of bend test specified in welding qualification specifications it is the only one that will be dealt with in this article.

Typical bend test jigs are illustrated in *Fig.1(a)* and *1(b)*.

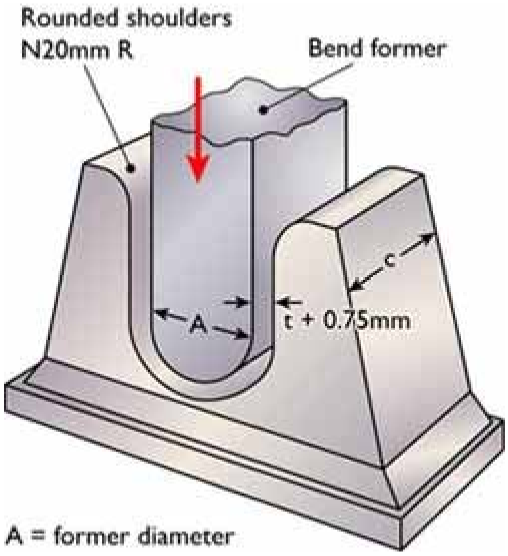
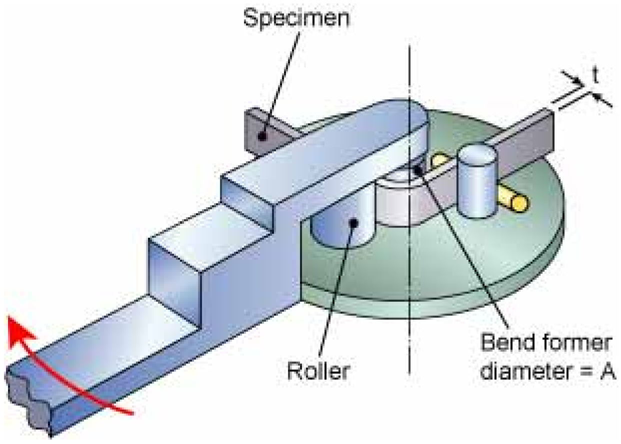



Fig.1(a) shows a guided bend test jig that uses a male and a female former, the commonest form of equipment

Fig.1(b) shows a wrap-around guided bend test machine that works on the same principles as a plumber's pipe bender




The strain applied to the specimen depends on the diameter of the former around which the coupon is bent and this is related to the thickness of the coupon 't', normally expressed as a multiple of 't' eg 3t, 4t etc.

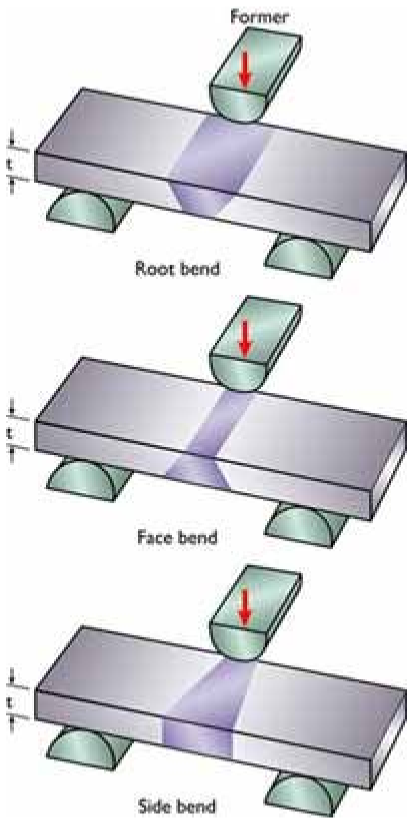
The former diameter is specified in the test standard and varies with the strength and ductility of the material - the bend former diameter for a low ductility material such as a fully hard aluminium alloy may be as large as 8t. An annealed low carbon steel on the other hand may require a former diameter of only 3t. The angle of bend may be 90°, 120° or 180° depending on the specification requirements.

On completion of the test the coupon is examined for defects that may have opened up on the tension face. Most specifications regard a defect over 3mm in length as being cause for rejection.

For butt weld procedure and welder qualification testing the bend coupons may be oriented transverse or parallel to the welding direction.

Below approximately 12mm material thickness transverse specimens are usually tested with the root or face of the weld in tension. Material over 12mm thick is normally tested using the side bend test that tests the full section thickness, *Fig. 2*.

Fig. 2.




Where the material thickness is too great to permit the full section to be bent the specifications allow a number of narrower specimens to be taken provided that the full material thickness is tested. Conventionally, most welding specifications require two root and two face bend coupons or four side bends to be taken from each butt welded test piece.

The transverse face bend specimen will reveal any defects on the face such as excessive undercut or lack of sidewall fusion close to the cap. The transverse root bend is also excellent at revealing lack of root fusion or penetration. The transverse side bend tests the full weld thickness and is particularly good at revealing lack of side-wall fusion and lack of root fusion in double-V butt joints. This specimen orientation is also useful for testing weld cladding where any brittle regions close to the fusion line are readily revealed.

Longitudinal bend specimens are machined to include the full weld width, both HAZs and a portion of each parent metal. They may be bent with the face, root or side in tension and are used where there is a difference in mechanical strength between the two parent metals or the parent metal and the weld. The test will readily reveal any transverse defects but it is less good at revealing longitudinally oriented defects such as lack of fusion or penetration.

Whilst the bend test is simple and straightforward to perform there are some features that may result in the test being invalid.

In cutting the coupon from the test weld the effects of the cutting must not be allowed to affect the result. Thus it is necessary to remove any HAZ from flame cutting or work hardened metal if the sample is sheared.

It is normal to machine or grind flat the face and root of a weld bend test coupon to reduce the stress raising effect that these would have. Sharp corners can cause premature failure and should be rounded off to a maximum radius of 3mm.


The edges of transverse bend coupons from small diameter tubes will experience very high tensile stresses when the ID is in tension and this can result in tearing at the specimen edges.

Weld joints with non-uniform properties such as dissimilar metal joints or where the weld and parent metal strengths are substantially different can result in 'peaking' of the bend coupon. This is when most of the deformation takes place in the weaker of the two materials which therefore experiences excessive localised deformation that may result in premature failure.

A dissimilar metal joint where one of the parent metals is very high strength is a good example of where this may occur and similar peaking can be seen in fully hard welded aluminium alloy joints.

In these instances the roller bend test illustrated in *Fig. 1(b)* is the best method of performing a bend test as each component of the coupon is strained by a similar amount and peaking is to a great extent eliminated.

## Related Specifications

BS EN 910 Destructive Tests on Welds in Metallic Materials - Bend Tests

| | |
|---|---|
| ASME IX | Welding and Brazing Qualifications |
| ASTM E190-92 | Guided bend Test for Ductility of Welds |

This article was written by Gene Mathers.

# Mechanical testing - notched bar or impact testing

Before looking at impact testing let us first define what is meant by 'toughness' since the impact test is only one method by which this material property is measured.

Toughness is, broadly, a measure of the amount of energy required to cause an item - a test piece or a bridge or a pressure vessel - to fracture and fail. The more energy that is required then the tougher the material.

The area beneath a stress/strain curve produced from a tensile test is a measure of the toughness of the test piece under slow loading conditions. However, in the context of an impact test we are looking at notch toughness, a measure of the metal's resistance to brittle or fast fracture in the presence of a flaw or notch and fast loading conditions.

It was during World War II that attention was focused on this property of 'notch toughness' due to the brittle fracture of all-welded Liberty ships, then being built in the USA. From this work the science of fracture toughness developed and gave rise to a range of tests used to characterise 'notch toughness' of which the *Charpy-V* test described in this article is one.

There are two main forms of impact test, the *Izod* and the *Charpy* test.

Both involve striking a standard specimen with a controlled weight pendulum travelling at a set speed. The amount of energy absorbed in fracturing the test piece is measured and this gives an indication of the notch toughness of the test material.

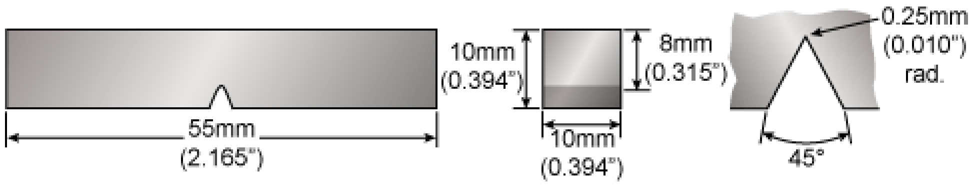
These tests show that metals can be classified as being either 'brittle' or 'ductile'. A brittle metal will absorb a small amount of energy when impact tested, a tough ductile metal a large amount of energy.

It should be emphasised that these tests are *qualitative*, the results can only be compared with each other or with a requirement in a specification - they *cannot* be used to calculate the fracture toughness of a weld or parent metal. Tests that can be used in this way will be covered in future *Job Knowledge* articles. The Izod test is rarely used these days for weld testing having been replaced by the Charpy test and will not be discussed further in this article.

The Charpy specimen may be used with one of three different types of notch, a 'keyhole', a 'U' and a 'V'. The keyhole and U-notch are used for the testing of brittle materials such as cast iron and for the testing of plastics. The V-notch specimen is the specimen of choice for weld testing and is the one discussed here.

The standard Charpy-V specimen, illustrated in *Fig. 1.* is 55mm long, 10mm square and has a 2mm deep notch with a tip radius of 0.25mm machined on one face.

Fig. 1. Standard Charpy-V notch specimen




To carry out the test the standard specimen is supported at its two ends on an anvil and struck on the opposite face to the notch by a pendulum as shown in *Fig. 2.* The specimen is fractured and the pendulum swings through, the height of the swing being a measure of the amount of energy absorbed in fracturing the specimen. Conventionally three specimens are tested at any one temperature, see *Fig. 3,* and the results averaged.

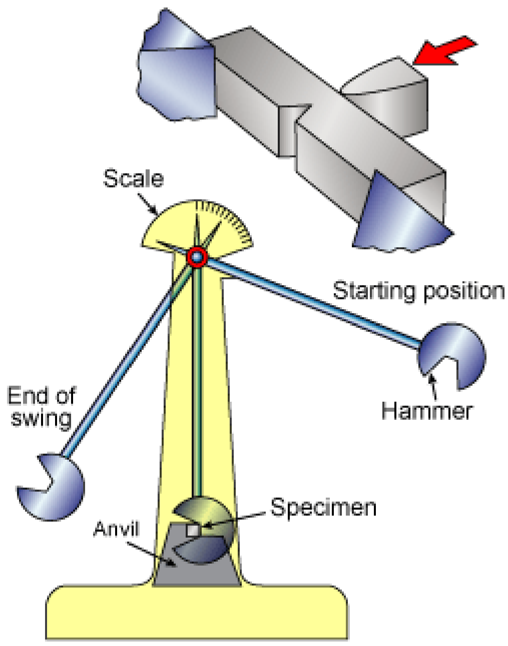



Fig. 2. Charpy testing machine

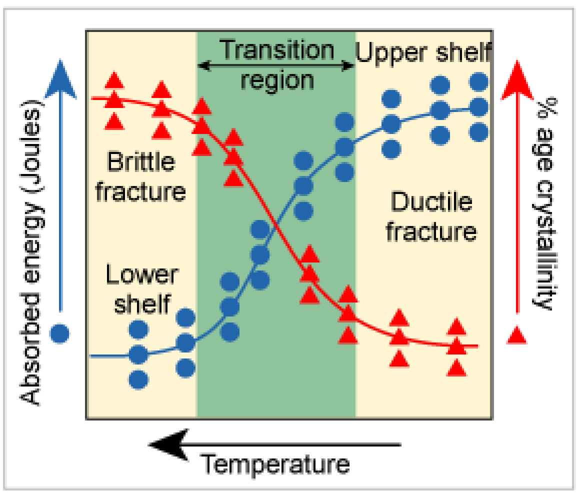



Fig. 3. Schematic Charpy-V energy and % age crystallinity curves

A characteristic of carbon and low alloy steels is that they exhibit a change in fracture behaviour as the temperature falls with the failure mode changing from ductile to brittle.

If impact testing is carried out over a range of temperatures the results of energy absorbed versus temperature can be plotted to give the 'S' curve illustrated in *Fig.3*.

This shows that the fracture of these types of steels changes from being ductile on the *upper shelf* to brittle on the *lower shelf* as the temperature falls, passing through a *transition* region where the fracture will be mixed.

Many specifications talk of a *transition temperature*, a temperature at which the fracture behaviour changes from ductile to brittle. This temperature is often determined by selecting, quite arbitrarily, the temperature at which the metal achieves an impact value of 27 Joules - see, for example the impact test requirements of EN 10028 Part 2 Steel for Pressure Purposes.

What the curve shows is that a ductile fracture absorbs a greater amount of energy than a brittle fracture *in the same material*. Knowing the temperature at which the fracture behaviour changes is therefore of crucial importance when the service temperature of a structure is considered - ideally in service a structure should operate at upper shelf temperatures.

The shape of the S curve and the positions of the upper and lower shelves are all affected by composition, heat treatment condition, whether or not the steel has been welded, welding heat input, welding consumable and a number of additional factors. All the factors must be controlled if good notch toughness is required. This means that close control of the welding parameters is essential if impact testing is a specification requirement.

Stainless steels, nickel and aluminium alloys do not show this change in fracture behaviour, the fracture remaining ductile even to very low temperatures. This is one reason why these types of alloys are used in cryogenic applications.

In addition to the impact energy there are two further features that can be measured and may be found as a requirement in some specifications. These are *percentage crystallinity* and *lateral expansion*.

The appearance of a fracture surface gives information about the type of fracture that has occurred - a brittle fracture is bright and crystalline, a ductile fracture is dull and fibrous.

Percentage crystallinity is therefore a measure of the amount of brittle fracture, determined by making a judgement of the amount of crystalline or brittle fracture on the surface of the broken specimen.

Lateral expansion is a measure of the ductility of the specimen. When a ductile metal is broken the test piece deforms before breaking, a pair of 'ears' being squeezed out on the side of the compression face of the specimen, as illustrated in *Fig 4*. The amount by which the specimen deforms is measured and expressed as millimetres of lateral expansion. ASME B31.3 for example requires a lateral expansion of 0.38mm for bolting materials and steels with a UTS exceeding 656N/mm $^2$ , rather than specifying an impact value.

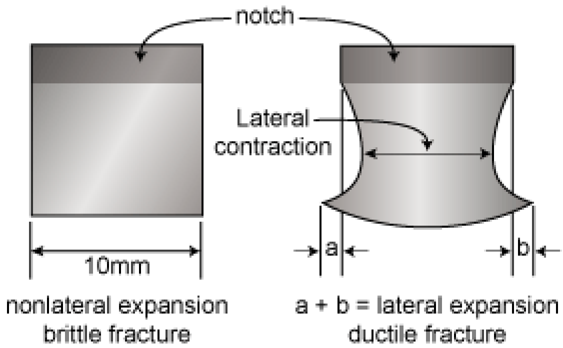



Fig.4 Lateral expansion

The next article in this series will look at the testing of welds, how the impact strength can be affected by composition and microstructure and some of its limitations and disadvantages.

This article was prepared by Gene Mathers.

# Notched bar or impact testing. Part II

The previous article looked at the method of Charpy-V impact testing and the results that can be determined from carrying out a test. This next part looks at the impact testing of welds and some of the factors that affect the transition temperature such as composition and microstructure. Within such a short article, however, it will only be possible to talk in the most general of terms.

Welding can have a profound effect on the properties of the parent metal and there may be many options on process selection, welding parameters and consumable choice that will affect impact strength.

Many application standards therefore require impact testing to be carried out on the parent metal, the weld metal and in the heat affected zone as illustrated in *Fig.1* which is taken from BS PD 5500 Annex D. The standards generally specify a minimum impact energy to be achieved at the minimum design temperature and to identify from where the specimens are to be taken. This is done in order to quantify the impact energy of the different microstructures in the weld metal and the HAZs to ensure that, as far as possible, the equipment will be operating at upper shelf temperatures where brittle fracture is not a risk.

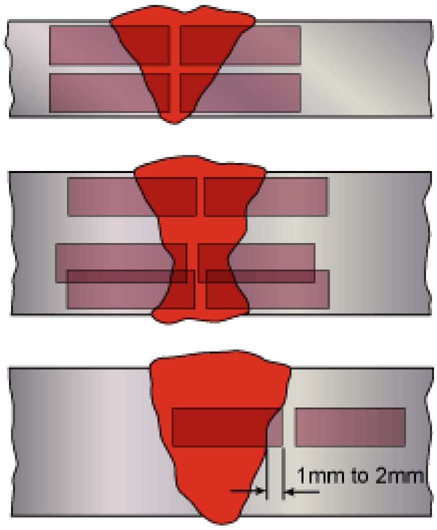



Fig.1. PD5500 App D. location of Charpy specimens in weld HAZ

These application standards may be supplemented by client specifications that impose additional and more stringent testing requirements, as shown in *Fig.2* taken from an oil industry specification for offshore structures.

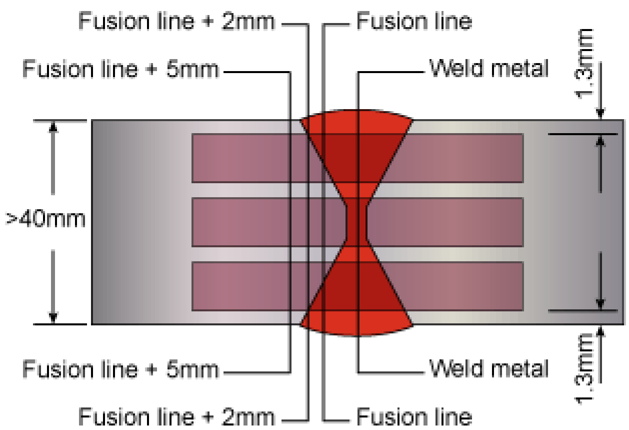



Fig.2. Offshore client requirements

The positioning of the specimens within a weld is extremely important both in terms of the specimen location and the notch orientation. A specimen positioned across the width of a multi-pass arc weld will probably include more than one weld pass and its associated HAZs. Quite a small movement in the position of the notch can therefore have a significant effect on the impact values recorded during a test. Positioning a notch precisely down the centre line of a single pass of a submerged arc weld can give extremely low impact values!

Testing the heat affected zone also has problems of notch position since in a carbon or low alloy steel there will be a range of microstructures from the fusion line to the unaffected parent metal. Many welds also use a 'V' preparation as illustrated above and this, coupled with the narrow HAZ, means that a single notch may sample all of these structures. If the impact properties of specific areas in the HAZ need to be determined then a 'K' or single bevel preparation may be used.

The standard specimen is 10mm x 10mm square - when a weld joint is thicker than 10mm the machining of a standard size specimen is possible. When the thickness is less than this and impact testing is required it becomes necessary to use sub-size specimens.

Many specifications permit the use of 10mm x 7.5mm, 5mm and 2.5mm thickness (notch length) specimens. There is not a simple relationship between a 10mm x 10mm specimen and the sub-size specimens - a 10mm x 5mm specimen does not have half the notch toughness of the full size test piece. As the thickness decreases the transition temperature also decreases, as does the upper shelf value, illustrated in *Fig. 3* and this is recognised in the application standards.

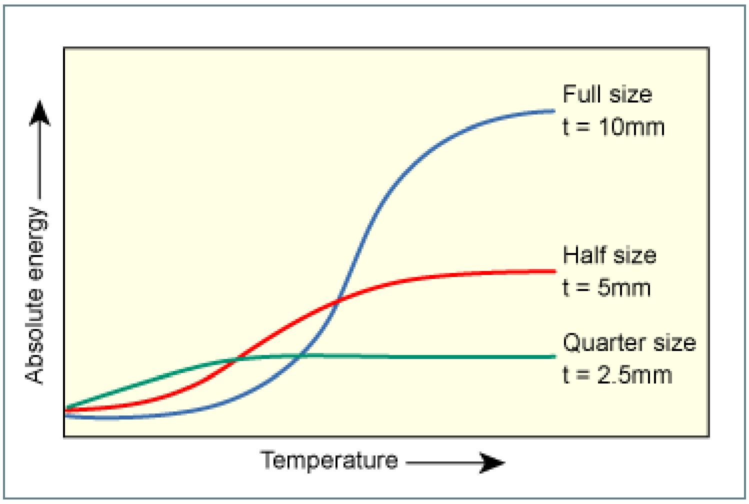



Fig. 3. Effect of size on transition temperature and upper shelf values

In a carbon or low alloy steel the lowest impact values are generally to be found close to the fusion line where grain growth has taken place.

Coarse grains generally have low notch toughness, one reason why heat input needs to be controlled to low levels if high notch toughness is required.

For example, EN ISO 15614 Pt. 1 requires Charpy-V specimens to be taken from the high heat input area of a procedure qualification test piece and places limits on any increase in heat input. Certain steels may also have an area some distance from the fusion line that may be embrittled so some specifications require impact tests at a distance of 5mm from the fusion line.

Charpy-V tests carried out on rolled products show that there is a difference in impact values if the specimens are taken parallel or transverse to the rolling direction. Specimens taken parallel to the rolling direction test the metal across the 'grain' of the steel and have higher notch toughness than the transverse specimens - one reason why pressure vessel plates are rolled into cylinders with the rolling direction oriented in the hoop direction.

In a carbon or low alloy steel the element that causes the largest change in notch toughness is carbon with the transition temperature being raised by around 14° C for every 0.1% increase in carbon content.

An example of how this can affect properties is the root pass of a single sided weld. This often has lower notch toughness than the bulk of the weld as it has a larger amount of parent metal melted into it - most parent metals have higher carbon content than the filler metal and the root pass therefore has a higher carbon content than the bulk of the weld.

Sulphur and phosphorus are two other elements that both reduce notch toughness, one reason why steel producers have been working hard to reduce these elements to as low a level as possible. It is not uncommon for a good quality modern steel to have a sulphur content less than 0.005%.

Of the beneficial elements, manganese and nickel are possibly the two most significant, the nickel alloy steels forming a family of cryogenic steels with the 9% nickel steel being capable of use at temperatures down to -196° C. Aluminium is also beneficial at around 0.02% where it has the optimum effect in providing a fine grain size.

Lastly, let us have a brief look at some of the other factors that can affect the impact values. These are concerned with the quality of the specimen and how the test is conducted.

It goes without saying that the specimens must be accurately machined, the shape of the tip of the notch being the most important feature. A blunted milling cutter or broach will give a rounded notch tip and this in turn will give a false, high impact value. Checking the tip radius on a shadowgraph is one simple way of ensuring the correct tip shape. Correct positioning of the specimen on the anvil is most important and this can be done using a specially designed former.

The last point concerns the testing of specimens at temperatures other than at room temperature. When testing at sub-zero temperatures the length of time taken to remove the specimen from the cooling bath, position it on the anvil and test it is most important. EN875 requires this to be done within five seconds otherwise the test piece temperature will rise making the test invalid - referring back to the impact energy vs temperature curve in the previous article will show why.

## Relevant Specifications

| | | |
|---|---|---|
| BS 131 | Part 4 | Calibration of Impact Testing Machines for metals. |
| BS 131 | Part 5 | Determination of Crystallinity |
| BS 131 | Part 6 | Method for Precision Determination of Charpy-V Impact Energy |
| BS 131 | Part 7 | Specification for Verification of Precision Test Machines |
| EN 875 | | Destructive Tests on Welds in Metallic Materials - Impact Tests |
| EN 10045 | Part 1 | Test Method |
| EN 10045 | Part 2 | Verification of Impact Testing Machines |
| ASTM E23-02A | | Standard Test Methods for Notched Bar Impact Testing of Metallic Materials. |

This article was written by Gene Mathers.