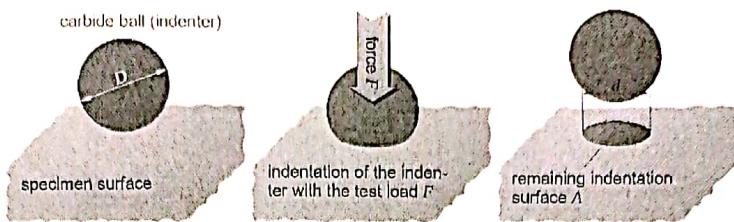


BRINELL HARDNESS TEST



With the Brinell hardness test, a carbide ball is pressed into the material. The indentation surface serves as a measure of the hardness!

Introduction

In many applications, components should have not only a high strength but also a high wear resistance. This generally applies whenever two or more components are in moving contact with each other. These include, for example, gears, shafts, bolts, pins, etc.

High wear resistance ultimately means a hard surface, so that the surface is not damaged in contact with adjacent components and thus wear is kept to a minimum. For this reason, characteristic values are required to characterize the hardness of a material. In order to obtain such parameters, hardness must first be defined:

Indentation hardness is the resistance of a material to penetration by an indenter (indentation resistance)!

According to this definition, all hardness testing methods are ultimately based on the same principle. An indenter (e.g. ball, cone, pyramid, etc.) is pressed with a certain force into the material surface to be tested. The indentation hardness value is determined from the indentation left behind.

Depending on the material to be tested and the given boundary conditions, different hardness tests have developed, whose respective measured values generally cannot be converted into one another. Therefore, hardness values can only be compared if they have been obtained by identical

test procedures. The most important procedures and their advantages and disadvantages are explained in more detail below:

- Brinell hardness test (explained in this article)
- Vickers hardness test
- Rockwell hardness test

Specially prepared specimens or real components can be used for hardness testing, provided that their functionality is not impaired due to the indentation left behind.

Determination of the hardness

In Brinell hardness testing, a hard metal ball (carbide ball) is pressed into the material surface to be tested within approximately 10 seconds as the force increases. The applied test force is maintained for 15 to 20 seconds so that the material can settle during this time and the measurement provides reproducible and comparable test results. The indentation left behind on the material surface is then determined under a light microscope. The ratio of testing force F and the indentation surface A (spherical segment) serves as a measure for the Brinell hardness value HBW:

$$HBW = \frac{0.102 \cdot F}{A} \quad (1)$$

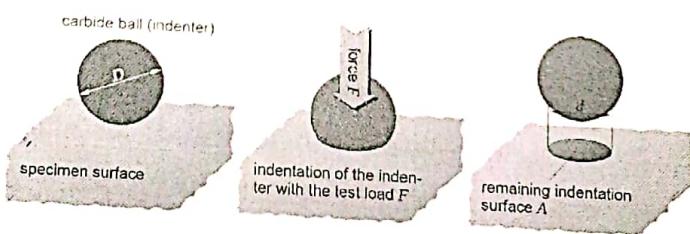


Figure: Brinell hardness test procedure

With the Brinell hardness test, a carbide ball is pressed into the material. The indentation surface left behind serves as a measure of the hardness!

The factor 0.102 in the equation is due to the unit "kilopond" or "kilogram-force" (1 kp \triangleq 9.807 N), which was used in the past but is no longer permissible today. Therefore, the unit kilopond was replaced by the physically correct unit "Newton" with the corresponding conversion factor of 0.102 (=1/9.807).

The indentation surface A can be determined by the diameter D of the penetrator ball and by the indentation diameter d left behind using the following formula:

$$A = \frac{\pi}{2} \cdot D \cdot (D - \sqrt{D^2 - d^2}) \quad (2)$$

By combining equation (2) and equation (1), the unit-less Brinell hardness HBW is calculated as a function of the applied penetration force F (in N) and the ball diameter D (in mm) and the indentation diameter d (in mm) as follows:

$$HBW = \frac{0.204 \cdot F}{\pi \cdot D \cdot (D - \sqrt{D^2 - d^2})} \quad \text{Brinell hardness} \quad (3)$$

Due to the anisotropy in the deformation behavior, it can happen that there is no exactly circular imprint on the material surface. Then the indentation diameter d is determined from the mean of two indentation diameters d_1 and d_2 at right angles to each other:

$$d = \frac{d_1 + d_2}{2} \quad (4)$$

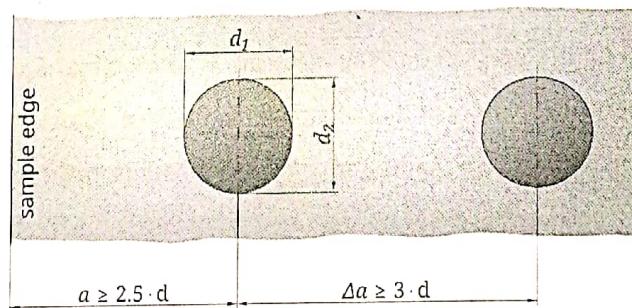


Figure: Minimum distances to be observed

Validity

To prevent the material from being pushed over the edge of the specimen during testing and therefore pretending a lower hardness value, the center of the indentation should be at least as far from the edge as 2.5 times the diameter of the indentation.

$$a \geq 2.5 \cdot d \quad (5)$$

If several hardness tests are carried out on one single specimen, care must be taken to ensure that the indentations do not fall below a minimum distance from each other. Otherwise, the measurement result would be influenced by hardening phenomena that occur around the respective indentations. This distance should not be less than 3 times the indentation diameter.

$$\Delta a \geq 3 \cdot d \quad (6)$$

In order to obtain comparable results, the indentation diameter d should not be smaller than 24 % and not larger than 60 % of the indenter diameter D :



$$0.24 \cdot D \leq d \leq 0.6 \cdot D \quad (7)$$

If the indentation diameters are too large and lie in the range of the test ball diameter, the test ball is pressed too deeply into the material. A further penetration then hardly produces a larger indentation diameter, which then leads to no longer reproducible hardness values due to measurement inaccuracies in the diameter determination.

If, on the other hand, the indentation diameter is too small compared to the test ball diameter used, however, the ball is hardly pressed into the material. Blurred edges are the result, from which it is very difficult to determine the indentation diameter left behind. Due to the low deformation, elastic portions are particularly high, so that the indentation diameter decreases relatively strongly when the ball is lifted off. The hardness values obtained from small indentation diameters are no longer valid, as well as those from large diameter values.

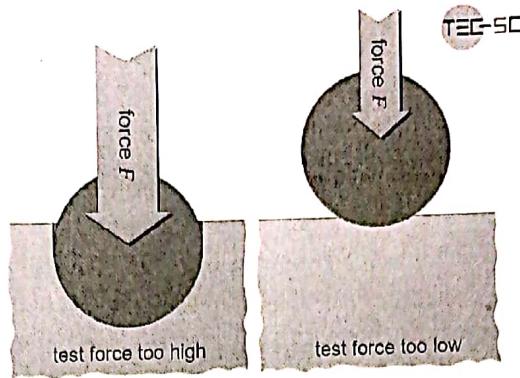


Figure: Too high and too low test loads

Load factor

For the above mentioned reasons of too much or too little penetration, the surface pressure between the ball and material sample must therefore not be too high and not too low. Comparable results for different materials are only given if the test was carried out with the same stress intensity. Due to the larger surface area, larger test balls also require higher test forces compared to smaller test balls, in which the forces are distributed over a smaller surface.

In order to do justice to this fact, the so-called *load factor* B is defined. The load factor is ultimately defined by the ratio of test load to test ball surface and can be regarded as a kind of "surface pressure":

$$B = \frac{0.102 \cdot F}{D^2} \quad \text{load factor} \quad (8)$$

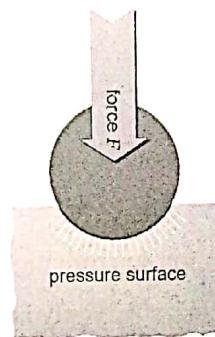


Figure: Illustration of the load factor

For comparability of the hardness values obtained with different test balls on different materials, the load factor B must have the same value in all cases!

The factor 0.102 results again from the obsolete unit "kilopond". In contrast to softer materials, hard materials must be tested with a higher load and thus with a higher load factor in order to maintain the diameter range according to the equation (7).

The load factor is standardized to the values 1 – 2.5 – 5 – 10 – 15 – 30. Depending on the expected hardness, reference values for the load factor used can be found in the table books. The test force F (in N) to be set can then be determined with equation (8) depending on the dimensionless load factor B and the selected ball diameter D (in mm).

Test balls

Sintered carbide balls with a standardized diameter of 10 mm, 5 mm, 2.5 mm, 2 mm or 1 mm are available as test balls for Brinell hardness testing. Small diameters are necessary for thinner sheets, as balls that are too large would only bulge out the material on the opposite side of the sheet. In principle, the sample thickness s should be at least 8 times the penetration depth h :

$$s \geq 8 \cdot h \quad \text{minimum thickness of the sample} \quad (9)$$

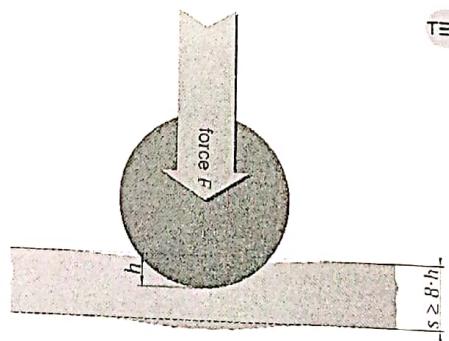


Abbildung: Bulging of a sheet metal during Brinell test

Large test balls are also not suitable for determining the hardness of thin surface layers. In such cases, there is a risk that the surface layer will only be pressed into the underlying base material.

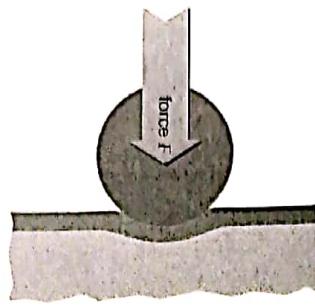


Figure: Testing of thin surface layers

Larger ball diameters are necessary when testing coarse-grained, heterogeneous microstructures (e.g. cast iron). Due to the large sphere, as many individual (heterogeneous) structural components as possible are involved in the deformation, resulting in a hardness value that covers the entire microstructure and not just individual phases. This testing of heterogeneous microstructures is a big advantage of Brinell hardness testing. In principle, however, it is only suitable for soft to medium-hard materials.

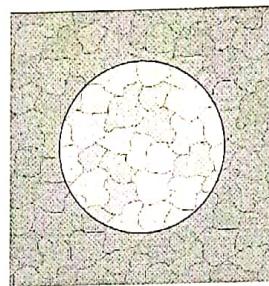


Figure: Testing of heterogeneous materials

Brinell hardness testing is particularly suitable for thicker, heterogeneous materials in the low to medium hardness range! Thin sheets cannot be tested with the Brinell hardness test!

The Brinell hardness test is not suitable for very hard materials or hardened surface layers because the ball does not penetrate sufficiently into the material. Higher test loads are not the solution at this point, as this leads to deformation of the carbide ball. The flattening of the ball results in a larger indentation diameter and thus pretends a softer material.

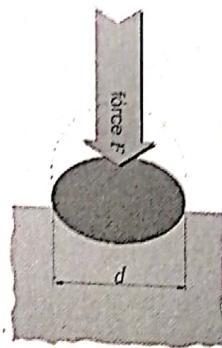


Figure: Flattening of the test ball

Even very thin sheets cannot be tested due to the aforementioned bulging of the material on the opposite side of the sheet. In order to close this gap, a new hardness test method was developed by Vickers, which is explained in a separate article.

Indication of the hardness value

The standard-compliant specification of Brinell hardness consists of the hardness value (HBW), the ball diameter (in millimeters), the test force (in kiloponds) and the application time (in seconds). These values are given without units and separated by slashes. The indication of the time can be omitted if the test was performed with the standard application time of 10 to 15 seconds.

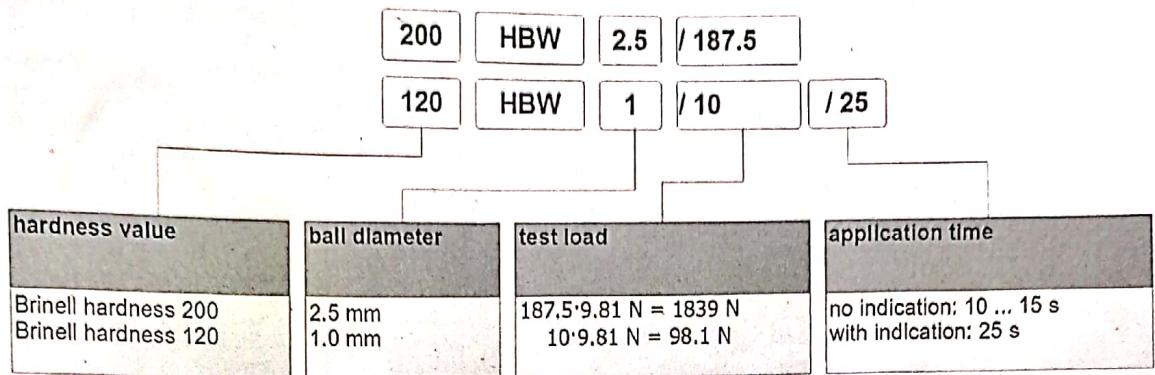


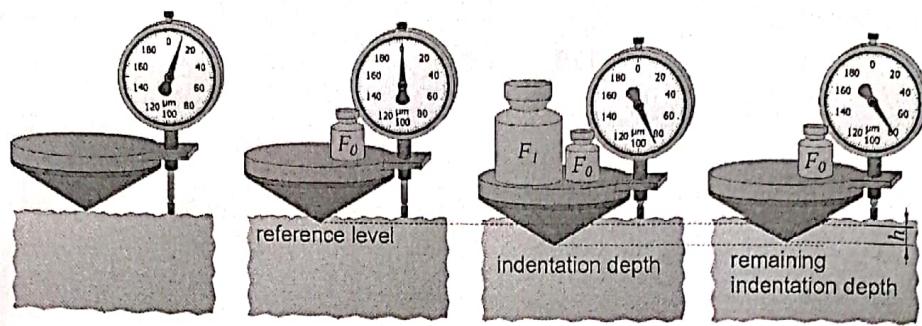
Figure: Standard-compliant specification of Brinell hardness value

Empirical relationship between tensile strength and hardness for non-alloy steels

For unalloyed and low-alloyed steels there is an empirical relationship between the Brinell hardness HBW and the tensile strength σ_u . This relationship means that the tensile strength (in N/mm²) corresponds approximately to 3.5 times the Brinell hardness value:

$$Rm \approx 3.5 \cdot HBW \quad (10)$$

ROCKWELL HARDNESS TEST



In the Rockwell hardness test, an indenter is pressed into the material. The indentation depth serves as a measure of the hardness!

In the Rockwell hardness test, the measure of the hardness is not an indentation surface but an indentation depth. Either a carbide ball or a rounded diamond cone with a tip angle of 120° and a tip radius of 0.2 mm serves as the indenter. The indentation depth can be read directly from a dial gauge via the traverse path of the testing machine.

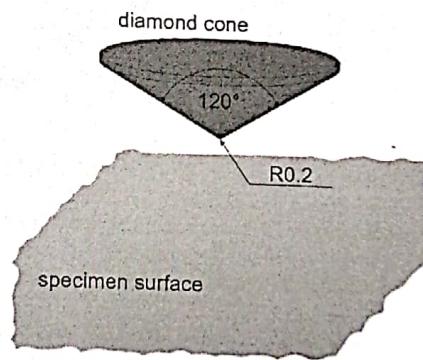


Figure: Diamond cone for Rockwell hardness testing

In the Rockwell hardness test, an indenter is pressed into the material to be tested. The indentation depth serves as a measure of the hardness!

The measuring process of the Rockwell test is carried out in three steps. First, the indenter is placed on the surface to be tested with a so-called *preload* F_0 of 98 N. In this way, the influences of

possible setting processes in the sample and any clearance in the measuring instrument can be compensated. After the preliminary test force has been applied for a short time, the dial gauge is set to zero (*reference level*). The actual hardness value can then be determined.

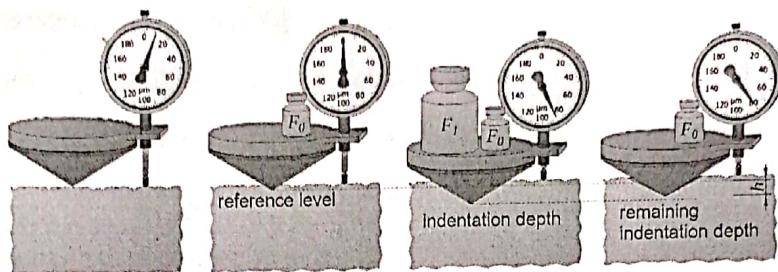


Figure: Rockwell hardness test procedure

The actual test load F_1 is applied in addition to the preload and the indenter penetrates the material with the total force $F = F_0 + F_1$. The test load to be set is taken from table books depending on the indenter and the material to be tested.

After the indenter has penetrated the material with a given total force, the test force F_1 is removed again. Finally, the material is only stressed by the preload F_0 and the indenter is slightly raised again by the elastic material behavior of the sample. However, contact with the sample remains. The remaining indentation depth h (in mm) while maintaining the preload F_0 is finally measured and used to determine the hardness value.

Depending on the indenter (diamond cone or carbide ball), the unit-less hardness value HR can be determined using the following formulae:

$$HRC, HRA = 100 - \frac{h}{0.002} \quad \text{Rockwell hardness for diamond cone} \quad (1)$$

$$HRB, HRF = 130 - \frac{h}{0.002} \quad \text{Rockwell hardness for carbide ball} \quad (2)$$

Testing with diamond cones

For diamond cones, the hardness value is obtained from a reference depth of 0.2 mm. Depending on how far the penetrated indenter reaches this reference depth, a corresponding hardness is assigned to the material. The complete penetration of the indenter to the reference depth obviously means a very soft material; this is assigned a hardness value of 0. If, however, the diamond cone does not penetrate the material at all, an extremely hard material is present, to which the full hardness value 100 is assigned. The scale follows an even subdivision of 0.002 mm (2 µm), so that reaching half the reference depth also corresponds to half the maximum hardness value (Rockwell hardness value 50). When diamond cones are used, the Rockwell scale is thus divided into 100 degrees of hardness.

The testing method with a diamond cone is particularly suitable for very hard materials such as hardened or tempered steels. Apart from special procedures, the preload is 98 N (10 kp). The actual test load can vary depending on the application.

In process variant C, the specimen is subjected to a test load of 1373 N (140 kp). However, especially when testing thin sheets, there is a risk that the material will only bulged out on the opposite side due to the high test force and thus falsify the measurement result. For this reason, variant A was introduced for diamond cone testing, which operates with a reduced test force of 490 N (50 kp). In addition, there is the less common variant D, in which the hardness value is determined using a test load of 883 N (90 kp). For its determination also equation (1) is used.

Note that in practice Rockwell hardness is not determined by equation (1) and (2) but read directly from a calibrated scale.

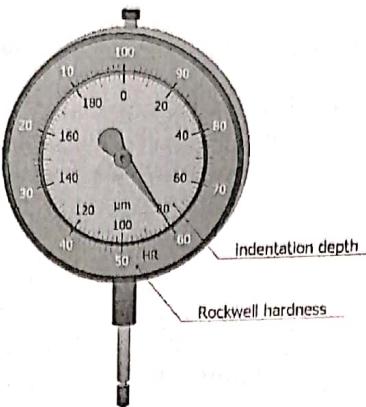


Figure: Dial gauge for the determination of the Rockwell hardness value

Testing with carbide balls

However, when testing relatively soft materials, the diamond cone would penetrate far too deeply into the material and would lie outside the reference depth of 0.2 mm. Therefore, soft surfaces are tested with carbide balls and the reference depth is extended to 0.26 mm. However, the division of the degrees of hardness in steps of 0.002 mm is maintained. This results in hardness values in the theoretical range of 0 (full indentation depth to 0.26 mm) to 130 (no indentation depth) when using carbide balls.

When using a carbide ball for hardness testing, a main distinction is made between process variants B and F. In contrast to diamond cone testing, they are suitable for softer metals such as construction steels or brass. The ball has a diameter of 1.5875 mm (=1/16 inches). In all process variants the preload is 98 N (10 kp). The procedures differ again only in the actual test load. In variant B the test load is 883 N (90 kp) and in variant F the test load is 490 N (50 kp). Due to its reduced test load, process variant F is particularly suitable for very soft materials such as copper or thin sheets.

Comparability of hardness values

Hardness values obtained with different process variants cannot be compared with each other. In addition, the hardness value obtained with a certain process method must lie within a certain range.

For values outside this range, the method should be changed because the indenter has either penetrated too strongly or too weakly into the material.

- HRC: 20 to 70
- HRA: 20 to 88
- HRB: 20 to 100
- HRF: 60 to 100

Advantages and disadvantages

The advantage of Rockwell hardness testing is the relatively short testing time and good automation capability, as the measured values are determined directly from the indentation depth without optical measurement under a microscope. This process is therefore particularly suitable for automated production.

A disadvantage of the Rockwell process is the relatively small depth range. Even small indentations in the material can lead to significant deviations in the indentation depth and thus in the hardness value. In addition, it is particularly difficult to differentiate between materials with high hardness values due to the small differences in depth.

Indication of the hardness value

The standard-compliant specification of Rockwell hardness consists of the hardness value and the test method.

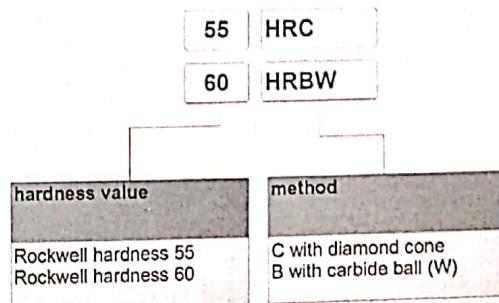
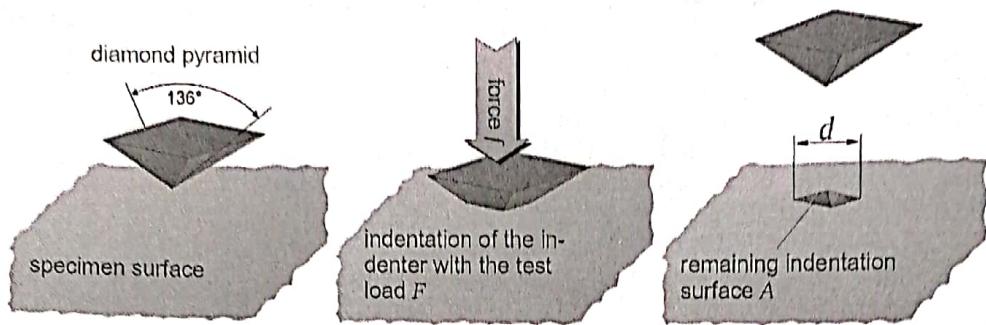


Figure: Standard-compliant indication of Rockwell hardness value

VICKERS HARDNESS TEST



In the Vickers hardness test, a four-sided diamond pyramid is pressed into the material. The indentation surface serves as a measure of the hardness!

For the Vickers hardness test, a square base pyramid with an *opening angle* of 136° is used as the indenter (opening angle = angle between two opposite surfaces of the pyramid). The angle was chosen so that the Vickers hardness values are comparable to a certain degree with the Brinell hardness values (applies to approx. 400 HBW or 400 HV). The diamond pyramid is pressed into the material surface with increasing force and maintained for about 10 to 15 seconds when the desired test force is reached. As with the Brinell hardness test, the ratio of test force F and indentation surface A (pyramid surface area) serves as hardness value for the Vickers method:

$$HV = \frac{0.102 \cdot F}{A} \quad (1)$$

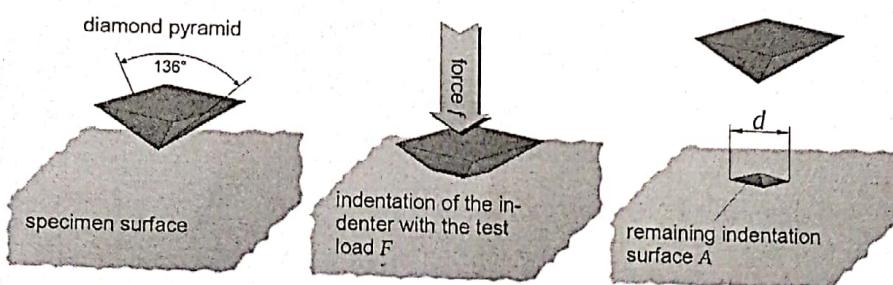


Figure: Vickers hardness test procedure

In the Vickers hardness test, a four-sided diamond pyramid is pressed into the material to be tested. The indentation surface left behind serves as a measure of the hardness value!

The factor 0.102 again comes from the no longer used unit "kilopond" (see Brinell hardness test). The indentation surface can be determined from the diagonals of the indentation left behind. With this indentation diagonal d (in mm) and the test force F (in N), the Vickers hardness value HV is then determined as follows:

$$HV = \frac{0.1891 \cdot F}{d^2} \quad \text{Vickers hardness} \quad (2)$$

The indentation diagonal d is determined by the mean value of the two diagonals d_1 and d_2 at right angles to each other:

$$d = \frac{d_1 + d_2}{2} \quad (3)$$

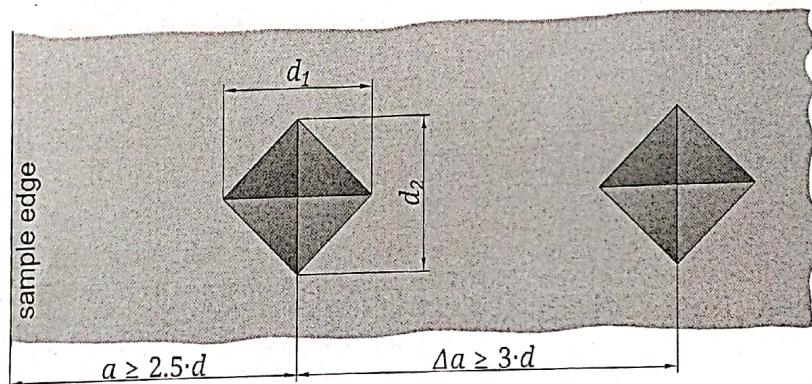


Figure: Minimum distance to be maintained

To avoid the risk of material bulging on the opposite side of the sample, the thickness should not fall below a certain minimum value. The minimum thickness depends on the expected hardness of the material and the test load.

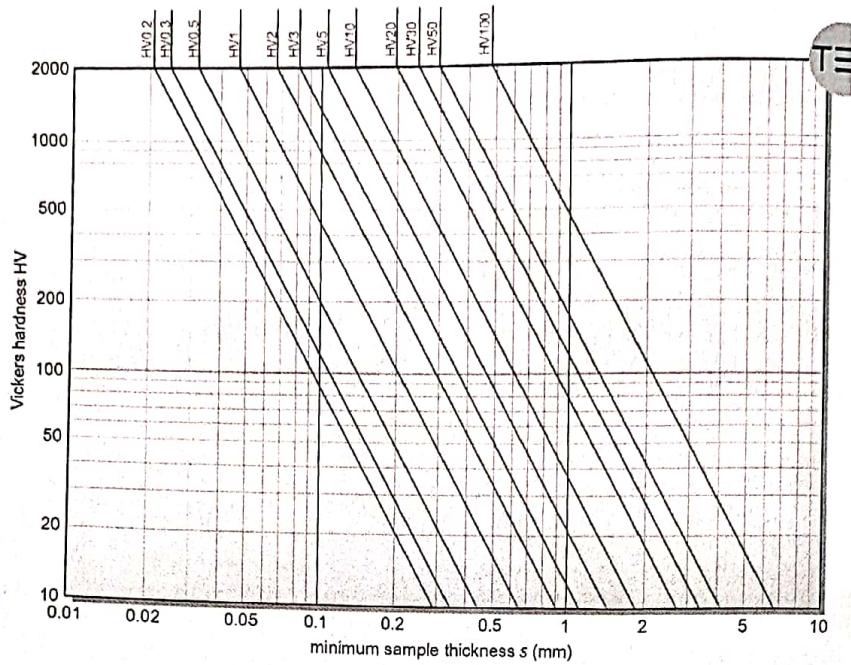


Figure: Minimum thickness of the sample as a function of hardness and test load

In addition, the distance a from the center of the indentation to the edge of the sample should be at least 2.5 times the value of the indentation diagonal d to prevent the material from flowing sideways:

$$a \geq 2.5 \cdot d \quad (4)$$

Furthermore, the distance between two adjacent indentations for steel and copper samples should be at least as far apart as three times the diagonal length of an indentation (six times for aluminum samples). This is to eliminate the influence of work hardening phenomena around the area of the indentation.

$$\Delta a \geq 3 \cdot d \quad (5)$$

Comparability of hardness values

In contrast to a ball (as in Brinell hardness test), a pyramid always provides to a certain extent geometrically similar indentations even with different test loads. Thus, with identical samples, the

double force also leads to a double indentation surface. As a ratio of force and indentation surface, the hardness value is therefore always identical despite different test loads*. However, the independence of the hardness value from the test load does not apply to low test loads. In this case, the elastic deformation accounts for a larger proportion of the total deformation. As a result, the remaining pyramid indentation is smaller and thus pretends a higher hardness value.

**) This is not the case with Brinell hardness test. There the double force (higher load factor) would lead to a different hardness value for the same ball used.*

Therefore, Vickers hardness values should only be compared with each other if they were determined with the same test loads. A harder material always requires higher test loads than a softer material. Depending on the expected hardness of the material, different test load ranges are prescribed. A distinction is made between three ranges of loads.

On the one hand, the so-called *macro test range* with test loads between 49.03 N (5 kp) and 980.7 N (100 kp), within which the hardness values are practically independent of the test load ("macro-hardness").

On the other hand, the *micro test range* is differentiated between 1.961 N (0.2 kp) and 29.42 N (3 kp). Such a load range is used for thin surface layers and sheet metals as well as for finished parts in order not to damage the components too much ("micro-hardness").

In special cases, the *nano test range* between 0.098 N (0.01 kp) and 1.961 N (0.2 kp) is also used ("nano-hardness"). The pyramid tip used offers an additional advantage over the ball in the Brinell process, since the pyramid-shaped indentation leaves sharper edges even at low indentation depths and can thus be better measured. At low indentation depths, therefore, the accuracy of the Vickers test increases compared to the Brinell hardness test.

In contrast to the Brinell hardness test, the Vickers test method is suitable for all hardness ranges, i.e. from very soft to very hard materials. In addition, this method can also be used for thin sheets or thin surface layers, which makes it a universal hardness testing method.

The Vickers hardness test is suitable for soft to very hard materials and especially for thin sheets!

Indication of the hardness value

The standard-compliant specification of Vickers hardness consists of the hardness value, the test force and the application time. The latter can be omitted with the standard time of 10 to 15 seconds.

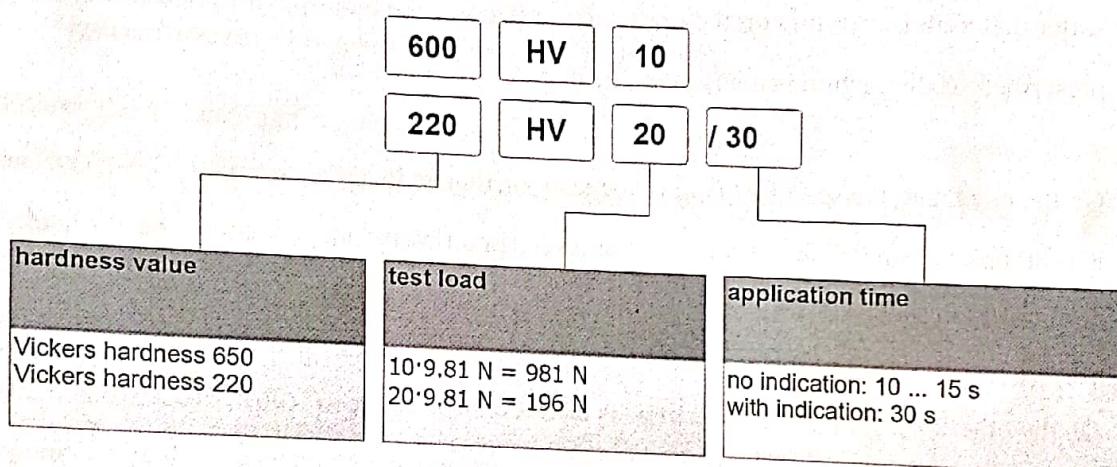


Figure: Standard-compliant specification of the Vickers hardness value

Both the Brinell and Vickers hardness test use the indentation surface left behind as a hardness measure. The indentation geometry is determined by a light microscope. This usually requires a glossy surface so that the indentation is clearly visible. It may be necessary to polish the sample before testing. Therefore, these processes are generally not suitable for automated production. For this reason, the Rockwell hardness test was developed.

Charpy and Izod Impact Tests

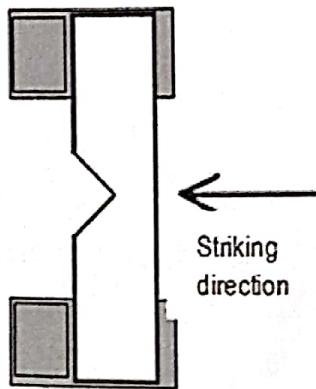
Summary

An impact blow is delivered to a test specimen by means of a pendulum-type hammer. The impact value of the material is determined from the energy required to break the specimen.

Testing method

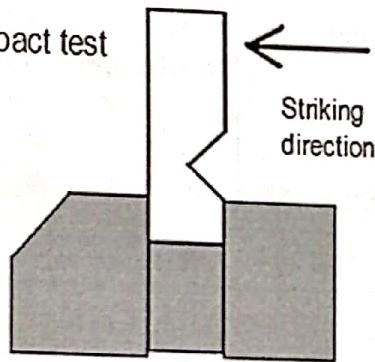
Testing method	Testable ranges	Test specimen	Data to be obtained	Corresponding standards
Charpy impact	Hammer capacity: 0.5,1,2,4,7.5,15J Test temp.: -40 - 150°C Impact speed : 0.5~4J $2.9(\pm 5\%) \text{m/sec}$ 7.5J, 15J $3.8(\pm 5\%) \text{m/sec}$	$80.0 \pm 2 \times 10.0 \pm 0.2$ $\times 4.0 \pm 0.2 \text{mm}^2$ n=5	Fracture energy (J) Impact strength (kJ/m^2)	JIS K7111-1 (ISO 179-1) JIS K6745 JIS K6911
Izod impact	Hammer capacity: 1,2,7.5,5.5J $40,80,150 \text{kg} \cdot \text{cm}$ Test temp.: -40 - 150°C Impact speed: $3.5(\pm 10\%) \text{m/sec}$	$80.0 \pm 2 \times 10.0 \pm 0.2$ $\times 4.0 \pm 0.2 \text{mm}^2$ $63.5 \pm 0.5 \times 12.7 \pm 0.1$ $\times 2 \quad 13 \text{mm}^2$ n=5	Fracture energy (J) Impact strength (J/m, kJ/m^2)	JIS K7110 (ISO 180) ASTM D256

Charpy impact test



A test specimen having a V-shaped notch is placed on the holder in such position that the notched section is in the center of the holder, and the specimen is broken by striking the back of the notched section with the hammer. The fracture energy is determined from the swing-up angle of the hammer and its swing-down angle. The Charpy impact value (kJ/m^2) is calculated by dividing the fracture energy by the cross-section area of the specimen.

Izod impact test



A test specimen having a V-shaped notch is fixed vertically, and the specimen is broken by striking it from the same side as that of the notch by the use of the hammer. The fracture energy is determined from the swing-up angle of the hammer and its swing-down angle. The Izod impact value (J/m , kJ/m^2) is calculated by dividing the fracture energy by the width of the specimen.

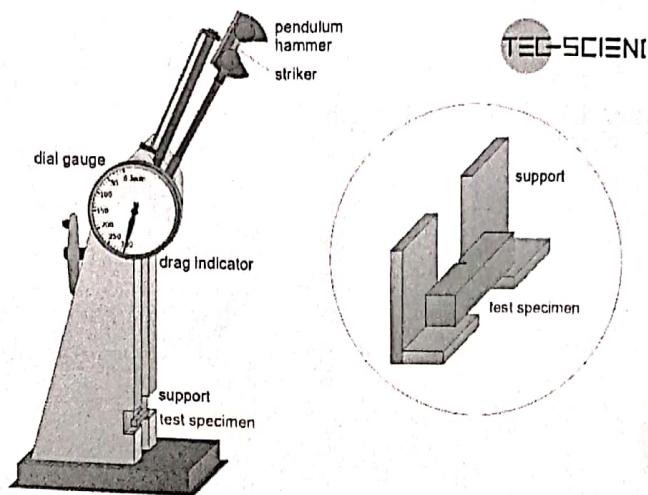
What can be known?

- The impact value can be used as a rule of thumb for determining the load bearing capacity of a material against momentary stress from impact strength and fracture energy.
- The higher the impact value of a material is, the higher the toughness or tenacity of the material is.

Examples of test specimens

Thermoplastic resins: PP, PC, PMMA, PS, ABS, PBT, NY, etc.
Composite materials: GFRP, CFRP, etc.

CHARPY IMPACT TEST



The Charpy impact test (Charpy V-notch test) is used to measure the toughness of materials under impact load at different temperatures!

Introduction

The *elongation at break* and *reduction in area* obtained by the tensile test can give an impression of the toughness of a material, but this only applies to a (quasi-)static load and only at room temperature. In many cases, however, components are also subjected to a shock load and not always at room temperature. This applies, for example, to shock absorbers and their bearings.

These components must withstand shock loads both in summer at high temperatures and in winter at extremely cool temperatures. The ideal boundary conditions of the tensile test can not meet reality. Components with good toughness behaviour in the tensile test become brittle at low temperatures and lead to premature material failure. For this reason, the so-called *Charpy impact test* or *Charpy V-notch test* is used to test the toughness of a material under an impact-like load as a function of temperature.

The Charpy impact test (Charpy V-notch test) is used to measure the toughness of materials under impact load at different temperatures!

Test setup and test procedure

In the Charpy impact test, a notched specimen is abruptly subjected to bending stress. The specimen is usually 55 mm long and has a square cross-section with an edge length of 10 mm. The notch in the middle has a V-shaped geometry (in special cases also U-shaped). The notch provides a defined predetermined breaking point, which generates a triaxial stress state in the notch base. The notched specimen is placed into the support of a *pendulum impact testing machine*.

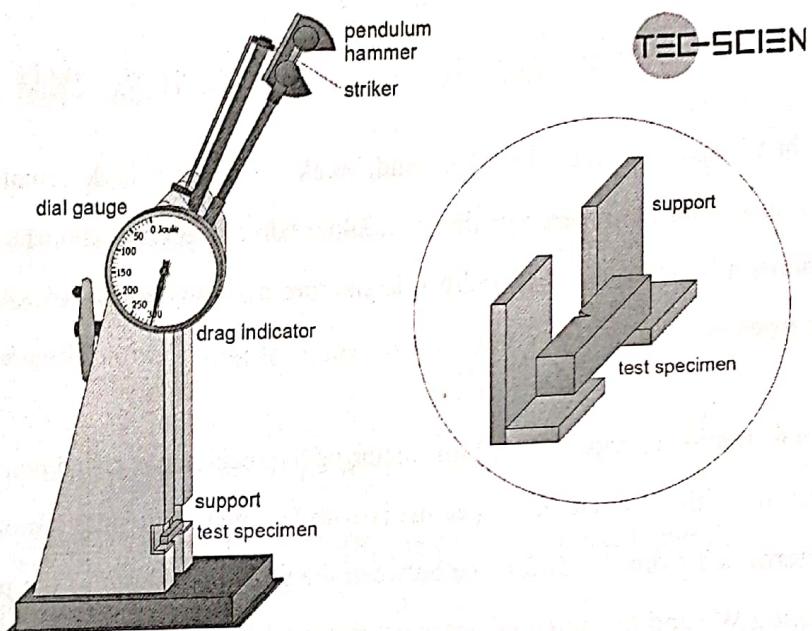
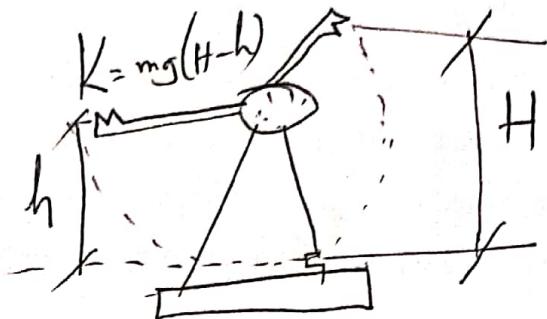


Figure: Test setup for Charpy impact test

A deflected pendulum hammer is then released from a certain height. At the lowest point of the circular trajectory, the striker of the hammer hits the opposite notch-facing side of the specimen (impact velocity usually between 5.0 and 5.5 m/s). The sample is fractured by the striker and absorbs part of the kinetic energy of the hammer. With the remaining residual energy, the hammer swings out to a certain height. Due to the absorbed kinetic energy through the sample, however, it does not reach its initial height again.

The deformation energy and thus the final height achieved depends on the toughness of the specimen. The tougher the material, the more it has to be deformed until it breaks. The required

deformation energies are correspondingly high and the pendulum energy is strongly absorbed. The hammer then only reaches a low final height after fracturing the specimen.



Animation: Charpy impact test (V-notch test)

Very brittle specimens, on the other hand, break almost without deformation and therefore require only a low deformation energy. The pendulum hammer swings almost at the initial level. Such a comparison between a tough and brittle fracture behavior is only possible if identical specimen geometries are used.

The deformation energy required for fracturing the specimen is called *notch impact energy* K (K_V : specimens with V-notch; K_U : specimens with U-notch). The notch impact energy can therefore be determined from the difference between the potential energy of the pendulum hammer at the beginning W_b and the potential energy at the end W_e .

The notch impact energy indicates the energy required to fracture a specimen and is therefore a measure of the toughness of a test specimen! Tough samples have higher notch impact energy values than brittle samples!

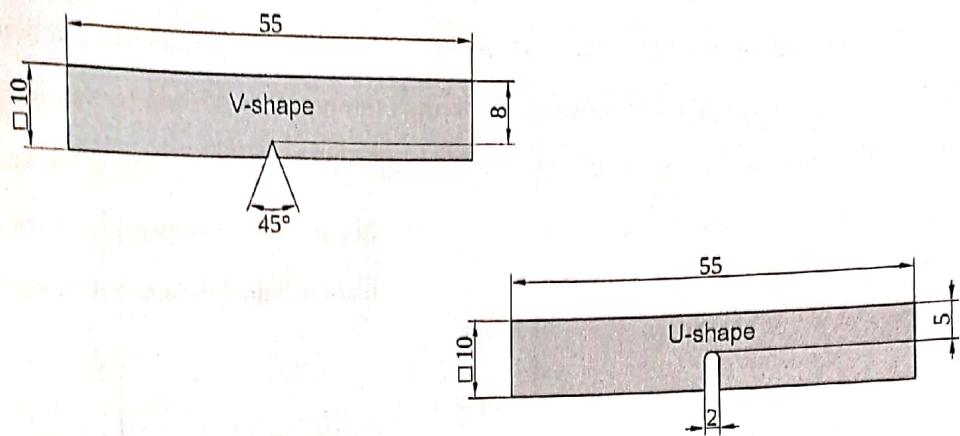


Figure: Specimen geometries for the Charpy impact test

At a given initial height H and mass m of the pendulum hammer, the notch impact energy depends only on the final height h . The notch impact energy can be read off directly from a dial gauge by a *drag indicator*, which is carried along from the lowest point as soon as the pendulum hammer hits the specimen.

$$K = Wb - We = m \cdot g \cdot H - m \cdot g \cdot h = m \cdot g \cdot (H - h) \quad (1)$$

$$K = m \cdot g \cdot (H - h) \quad [K_V] = J \quad \text{notch impact energie} \quad (2)$$

The notch impact energy determined in this way strongly depends on the cross-sectional area of the specimen. Large cross-sections always require higher deformation energies than smaller ones, even if under certain circumstances a more brittle behavior is present. Comparisons in toughness by the notch impact energies are therefore only possible if they were obtained from identical specimen geometries. If at all, a comparison with different geometries is only possible if the notch impact energy K is related to the cross-section A_K of the specimen. This quotient of notch impact energy and cross-sectional area is often referred to as *notch toughness* α , although in most cases this term is used identically to that of notch impact energy.

$$\alpha = \frac{K}{K_V}; \quad [\alpha] = \frac{J}{mm^2} \quad \text{notch toughness} \quad (3)$$

Note that even notch toughness α_a is not a pure material parameter, as it is not dependent on the material alone. The notch impact energy and thus the notch toughness is also influenced by the shape of the specimen cross-section and in particular by the shape of the notch and the speed at which the hammer hits the specimen (more on this in the section on *fracture types*). Thus, notch impact energy and notch toughness are purely technological parameters that are not included in any dimensioning calculations.

Notch impact energy values are technology parameters and can only be compared with each other if they were obtained from identical specimen geometries with identical boundary conditions (e.g. impact speed, temperature, notch shape, etc.)!

Upper shelf, lower shelf and transition temperature

However, the mentioned influences on notch impact energy, such as fracture speed, temperature and notch shape, are only of minor significance with regard to the actual objective of the Charpy impact test. This is because the V-notch test serves less to compare different materials with each other than to qualitatively compare the toughness of a single material at different temperatures!

In this way, it is possible, for example, to determine at what temperature a material becomes brittle in order to specify the limits of use of the material. For this purpose, the Charpy impact test must only be carried out sufficiently often on samples of the same material at different temperatures. If this is done in this way, especially materials with a body-centered cubic lattice structure (bcc) such as ferritic steels and materials with hexagonal lattice structures (hex) show a particularly strong dependence of toughness on temperature.

While these materials have high toughness at high temperatures, they become brittle at low temperatures. Many plastics show such a behaviour as well, which also begin to become brittle at low temperatures, while they are relatively tough at high temperatures. This behaviour can be illustrated graphically by plotting the notch impact energy as a function of the temperature.

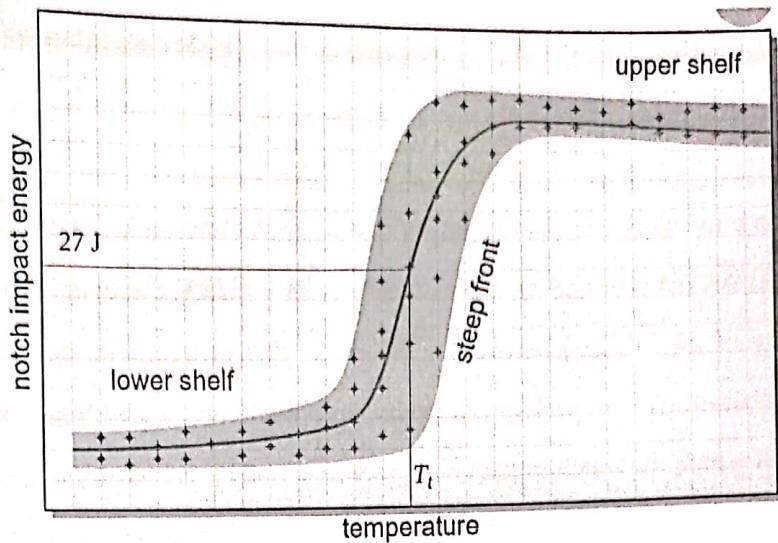


Figure: Notch impact energy as a function of temperature

In body-centered cubic and hexagonal lattice structures, the notch impact energy values are very strongly dependent on temperature! For such materials, the brittleness behavior is therefore strongly influenced by temperature!

The temperature range at which the specimen has low notch impact energy values and thus behaves brittle is referred to as *lower shelf*. Accordingly, the *upper shelf* indicates the temperature range at which the material behaves relatively tough. Between the lower and the upper shelf there is a transition range, which is characterized by strongly scattering values.

The reason for the large scattering in the transition area lies in small microstructural differences between the individual samples, which cause the material to become brittle at slightly higher or lower temperatures. Therefore, the toughness scatters very strongly despite identical temperatures. Due to the steeply sloping curve from upper shelf to lower shelf, this transition range is also referred to as *steep front*.

Due to the continuous curve from the upper to the lower shelf, no specific temperature can be assigned to this transition. Nevertheless, different approaches are used to define such a *transition*

temperature in order to identify the temperature below which embrittlement of the material is to be expected.

The transition temperature is frequently defined by the notch impact energy itself. The transition temperature T_t is often defined as the temperature at which the specimen has an average notch impact energy of 27 J ($T_{t,27J}$). However, values of 40 J or 60 J can also be used to define the transition temperature ($T_{t,40J}$ or $T_{t,60J}$). It is also possible to define the transition temperature as the temperature at which the notch impact energy corresponds to 50 % of the upper shelf.

The transition temperature is the temperature below which a material sample shows a rather brittle behaviour in the Charpy impact test and above the transition temperature a rather tough one!

In comparison to materials with body-centered cubic lattice structures, the temperature has hardly any influence on the toughness for materials with face-centered cubic lattice structures such as aluminium. With such materials there is no pronounced lower or upper shelf and therefore no steep front! Some materials behave relatively tough over the entire temperature range, such as aluminium, or show relatively brittle behaviour, such as hardened steels (not tempered) or lamellar graphite castings.

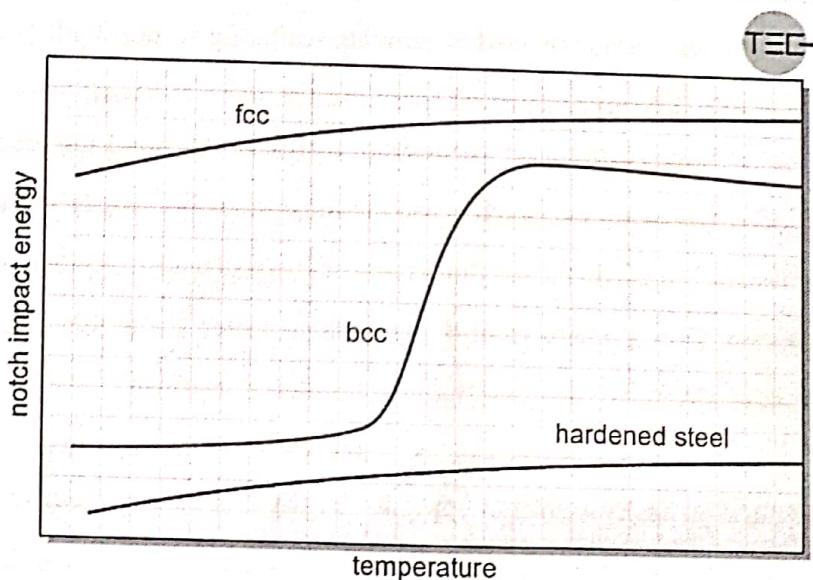


Figure: Notch impact energy as a function of temperature for different lattice structures

Materials with face-centered cubic lattice structures generally do not show a pronounced upper or lower shelf; they behave either brittle or tough over a wide temperature range!

Testing of state structure

Toughness is not only influenced by temperature but also by the structural state of the material. Quenched and tempered steels and fine-grained structural steels, for example, are characterised by their special toughness. Compared to normalized steels, this remains unchanged even at lower temperatures. The steep front in quenched and tempered steels therefore shifts to lower temperatures. In this way, the Charpy impact test can also be used to check heat treatments or structural conditions.

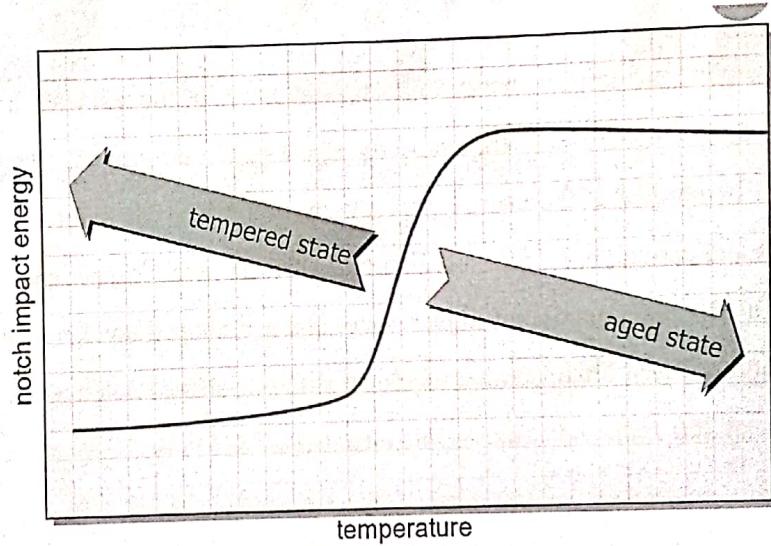


Figure: Influence of structural changes on the transition temperature

The reverse effect on the position of the steep front in steels is caused by aging. Aging leads to embrittlement and consequently shift the transition temperature to higher values. Thus, the influence of aging effects can also be examined in the Charpy impact test. Hardened steels also show a shift in transition temperature to higher values due to their low toughness.

The Charpy impact test can also be used to check state structures (heat treatment, aging, etc.)!

In summary, the Charpy impact test may have the following objectives:

- Determination of the transition temperature (onset of possible embrittlement)
- Verification of heat treatments
- Examination of aging effects

Indication of notch impact energy values

In addition to the notch impact energy value, the indication of the test result shall also include the notch shape and possibly the energy capacity of the pendulum impact tester (Wb). The energy capacity can be omitted if the energy capacity corresponds to the standard value of 300 J. For example, the indication "KV 150 = 40 J" means that the notch impact energy was 40 J in total when using a 150-Joule pendulum impact tester and a V-shaped notched specimen. If the notch impact energy had been obtained on a specimen with a U-shaped notch and a standard pendulum impact tester of 300 J, the indication would have been: "KU = 40 J".

Fracture types

The fracture behaviour of the specimens used cannot only be assessed on the basis of the notch impact energy. Even the form of the fracture provides information about the toughness or embrittlement of the specimen.

A very tough behaviour can be seen by a strongly deformed fracture surface. Often the ductile sample is not even divided into two parts but only pulled through the two supports in a strongly deformed state. Such a fracture on the upper shelf is therefore also called a *deformation fracture* or *sliding fracture*. The fracture surface of steels appears in a matt grey. Under the microscope, the fracture surface shows a honeycomb-like structure.

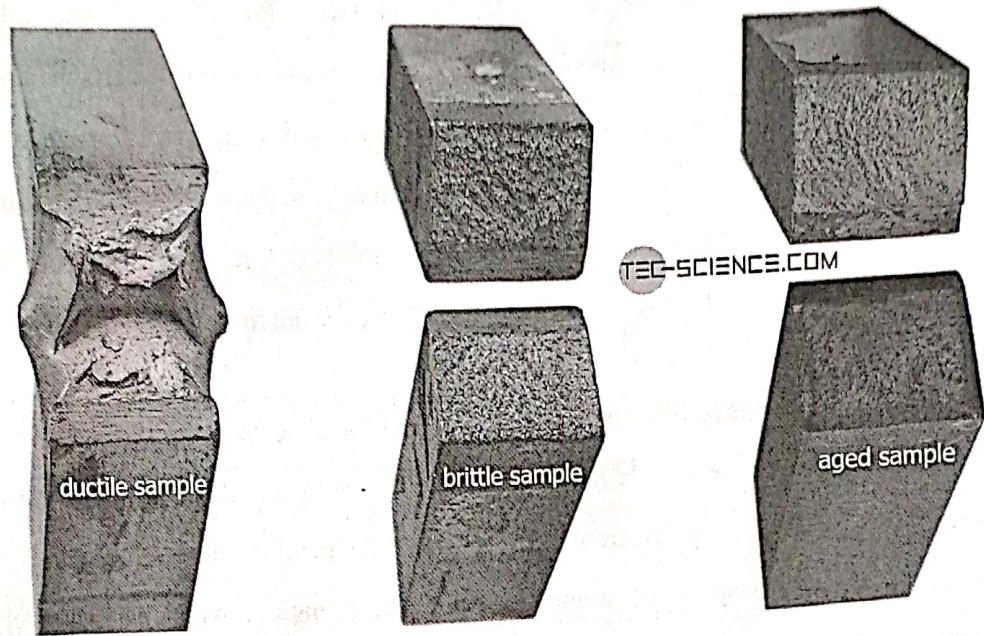


Figure: Deformation fracture (left), brittle fracture (center) and fracture of an aged sample (right)

Deformation fracture (sliding fracture) is the fracture of a tough specimen in which the fracture surface shows very strong deformation (high notch impact energy values)!

On the lower shelf, however, there is hardly any deformation. The sample is usually separated in two halves when the hammer strikes. Such *brittle fracture* is also referred to as *cleavage fracture*. The fracture surface appears shiny whitish. In the transition temperature range, the fracture surface often shows characteristics of both types of fracture, i.e. a strongly deformed area followed by an area with less deformation. This type of fracture is then also referred to as *mixed fracture*.

Brittle fracture (cleavage fracture) is the fracture of a brittle specimen in which the fracture surface shows only slight deformation (low notch impact energy values)!

Influence of impact speed on notch impact energy

As far as impact load and specimen geometry are concerned, the Charpy impact test is carried out under precisely defined conditions. Therefore, the results cannot easily be applied to real situations. The deformation speed (impact speed) also has a major influence on the fracture behaviour. If the pendulum hammer hits the specimen at higher speeds, brittle fracture is favoured and the notch impact energies decrease. Conversely, lower deformation speeds are more likely to lead to a deformation fracture with correspondingly higher notch impact energy values.

Due to high impact speeds, the stress in the material increases so rapidly that the bond strength (cohesion strength) of the atomic planes is exceeded before the dislocations could have moved through the material to a significant extent. Note that dislocations do not move infinitely fast but can only move at the speed of sound! A plastic deformation, which is ultimately based on dislocation movements, therefore does not take place at very high deformation speeds. The material breaks practically without deformation by tearing apart the atomic planes (cleavage fracture). Preference is given to those atomic layers that are relatively loosely packed.

Brittle fracture is favoured by high deformation speeds!

At slow deformation speeds, however, the dislocations can move over long distances and deform the material when the critical shear stress is reached. The material is then plastically deformed before it fractures (*deformation fracture*).