Mechanical testing methods

Materials testing studies the behaviour of materials under different loads. In particular, the relationship between the acting forces and the resulting deformation and the limit stresses that lead to failure of components are considered.

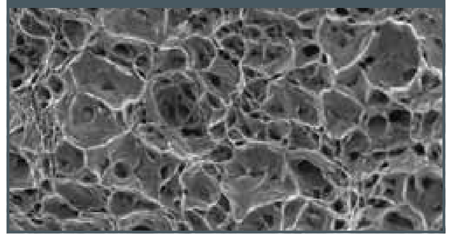
The characteristic values obtained from the testing process are used for materials development, designing components and in quality assurance. There is a range of standardised testing methods to characterise the mechanical properties of materials as precisely as possible:

Mechanical property	Testing method
Elasticity, plasticity	Tensile test, compression test, bending test, torsion test
Stiffness, material behaviour under static load	
Creep behaviour	Creep rupture test
Hardness	Brinell, Rockwell, Vickers
Toughness	Impact test
Fatigue behaviour, fatigue strength	Wöhler fatigue test

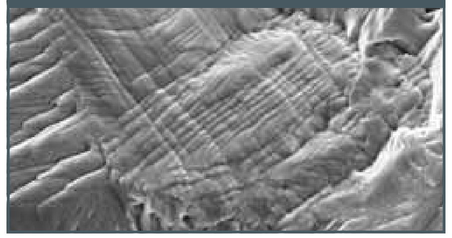
The fracture behaviour is used to characterise the material.
The summary below shows a relationship between failure mechanism and stress:

Fracture type	Fracture mechanism	Stress
Forced fracture ■ occurs abruptly ■ matte or glossy crystalline and partially fissured surface over the entire cross section; in ductile fractures, shear lips often occur at the edge	**Static overstress** **a)** low-deformation cleavage fracture occurs when the largest direct stress exceeds the cleavage fracture stress **b)** ductile fracture (microscopic honeycomb fracture) occurs when the largest shear stress exceeds the yield stress **c)** a low-deformation intergranular fracture can occur with a reduction of the grain boundary cohesion under the influence of direct stress	Tensile test, impact test
Fatigue fracture ■ can develop following repeated stress under the influence of shear or direct stress ■ low-deformation fracture	**Dynamic overstress** Starting from notches or imperfections, oscillatory cracks propagate through the material. When the material strength is exceeded, the remaining surface fractures by way of a forced fracture.	Wöhler fatigue test
Creep fracture ■ continuous time-dependent process ■ sets in at higher temperatures and eventually leads to fracture, although the material is loaded below the hot yield point ■ pores on grain boundaries lead to material damage	**Static stress, e.g. increased temperature** Countless cracks form independently of each other	Creep rupture test

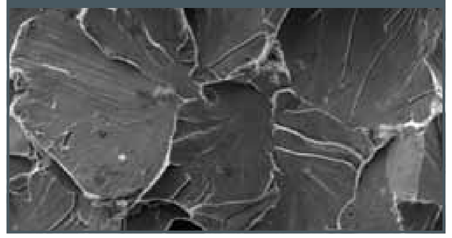
Honeycomb fracture



Fatigue fracture

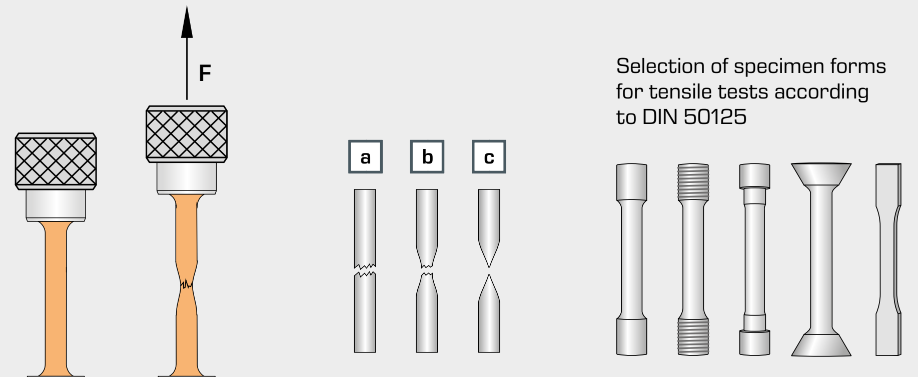


Cleavage fracture



Tensile test to determine the tensile strength and elongation at fracture

The tensile test is the most important testing method in destructive materials testing. A standardised specimen with a known cross section is loaded uniformly with relatively low increasing force in the longitudinal direction. A uniaxial stress state prevails in the specimen until contraction commences. The ratio of stress to strain can be shown from the plotted load-extension diagram.

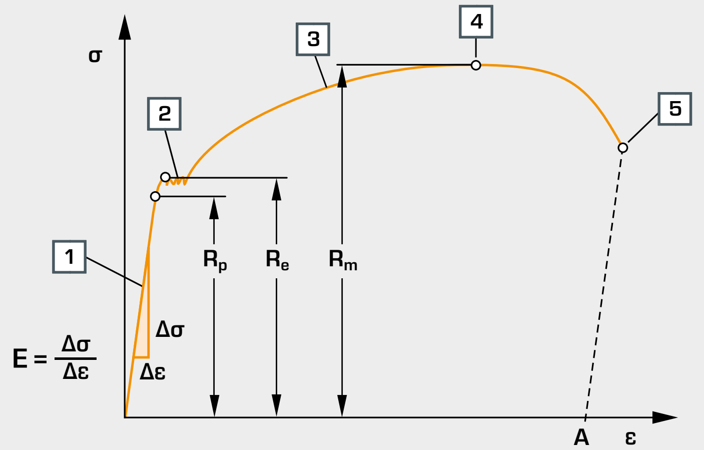


Test process of a classic tensile test

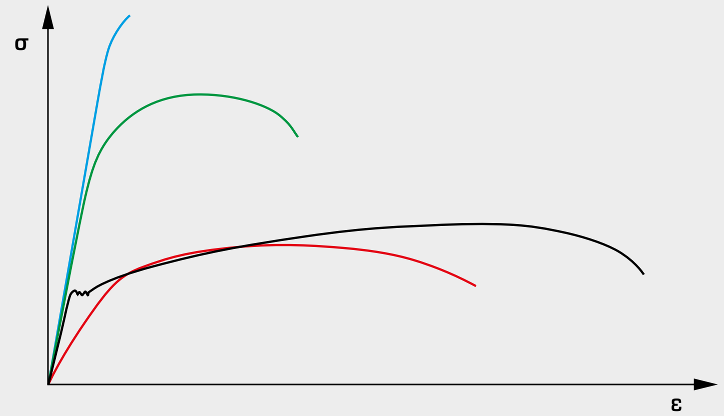
F force, **a** low-deformation fracture, **b** ductile fracture, **c** completely ductile fracture

Stress-strain diagram

The stress-strain diagram shows clearly the different behaviour of the individual materials and provides the characteristic values for tensile strength $\mathbf{R_m}$, yield strength $\mathbf{R_e}$, proportional limit $\mathbf{R_p}$, elongation at fracture **A** and the elastic modulus **E**.



σ stress, **ε** strain, $\mathbf{R_p}$ proportional limit, $\mathbf{R_e}$ yield strength, $\mathbf{R_m}$ tensile strength, **A** elongation at fracture
1 Hooke's straight line, **2** Lüders strain, **3** strain hardening region, **4** start of contraction, **5** fracture

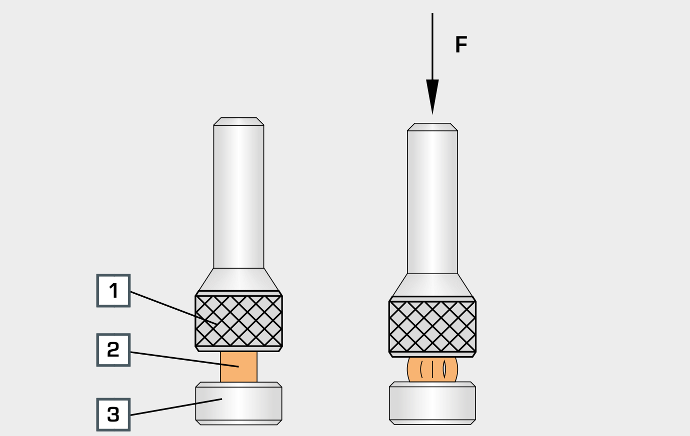


Every material has a characteristic profile of stress and strain.

- hardened steel: very high tensile strength
- tempered steel: high tensile strength
- low-strength steel: very high elongation, low tensile strength
- aluminium alloy: low elastic modulus

Mechanical testing methods

Compression test to determine flow curves

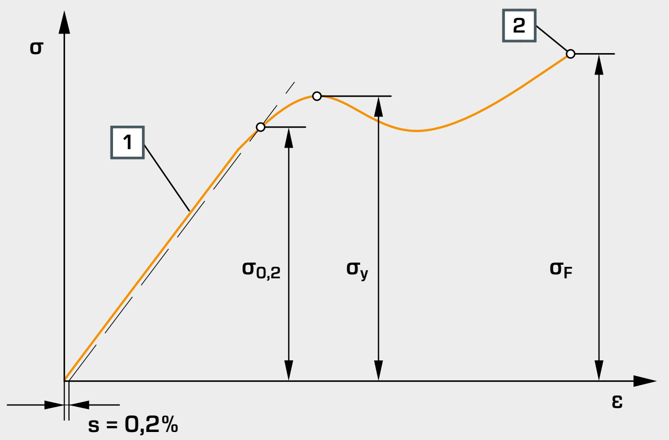


Test process in the compression test

1 thrust plate, **2** specimen, **3** pressure plate, **F** test load

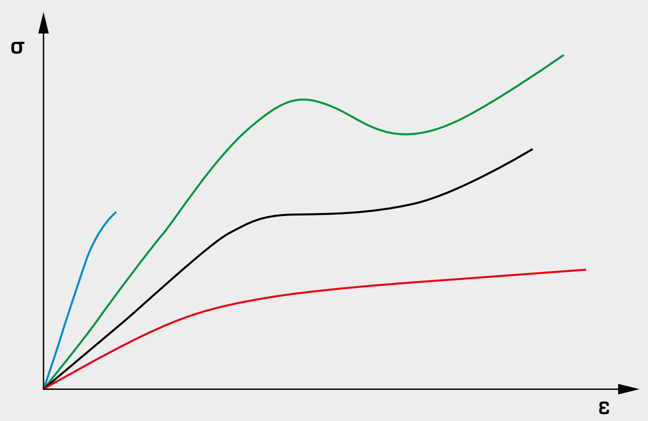
Compression tests are less significant for testing metallic materials compared to tensile tests. However, when studying building materials such as natural stone, brick, concrete, wood etc., the compression test is fundamentally important. A standardised specimen with a known cross section is loaded uniformly with low increasing force in the longitudinal direction. A uniaxial stress state prevails in the specimen. The ratio of stress to compression can be shown from the plotted force-path diagram. The **stress-compression diagram** shows clearly the different behaviour of the various separate materials and provides the characteristic values for compression strength, 0,2% offset yield point and the compression yield stress.

Stress-compression diagram



Stress-compression diagram

σ stress, ε compression, **s 0,2%** offset yield point, σ_y compression yield stress, σ_F compression strength, **1** elastic region, **2** fracture



Every material has a characteristic profile of compression and stress.

- brittle plastic, no compression strength
- ductile plastic with compression yield stress
- ductile plastic without compression yield stress
- ductile plastic without fracture

Various methods for determining hardness

Hardness refers to the mechanical resistance with which a body opposes the intrusion of another body.

Principle of the Brinell hardness test

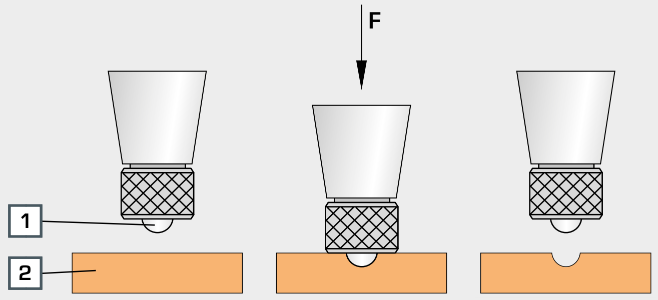
In this test method, a standardised test body – a hard metal sphere – is pressed into the workpiece under defined conditions. The surface of the lasting impression is then measured optically. The impression surface is calculated from the impression diameter and the sphere diameter. A triaxial stress state develops in the specimen, underneath the impressing test body.

The Brinell hardness is calculated from the test load and impression surface of the spherical segment.

$$HB = \frac{0{,}102 \cdot F}{A_B} \qquad 0{,}102 = \frac{1}{9{,}81} = \frac{1}{g}$$

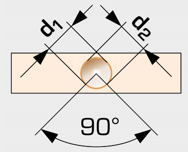
to convert N into kgf

HB Brinell hardness value, **F** test load in N, A_B impression surface in mm^2, **g** = 9,81 gravitational acceleration



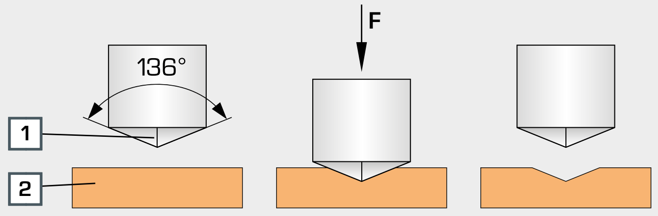
Test process and optical measurement of the permanent indentation

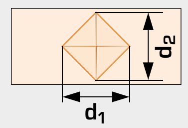
1 hard metallic sphere, **2** specimen, **F** test load, d_1 and d_2 diameters perpendicular to each other



Principle of the Vickers hardness test

The test method is similar to the Brinell hardness test. Unlike the Brinell method, a pyramid-shaped diamond is used as the test body. The impression diagonal is determined by measuring the two diagonals d_1 and d_2 and by taking the average. The Vickers hardness is the quotient of the test load and impression surface.



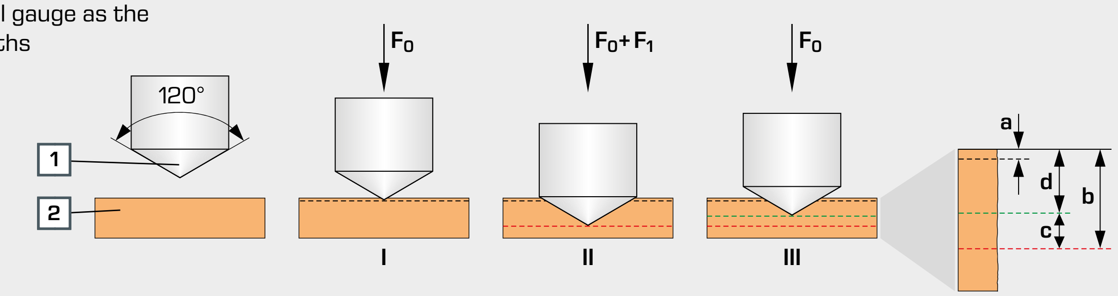


Test process and optical measurement of the permanent indentation

1 pyramid-shaped diamond, **2** specimen, **F** test load, d_1 and d_2 diagonals

Principle of the Rockwell hardness test

Rockwell's hardness test method allows the hardness to be read directly on a dial gauge as the difference of the depths of penetration.



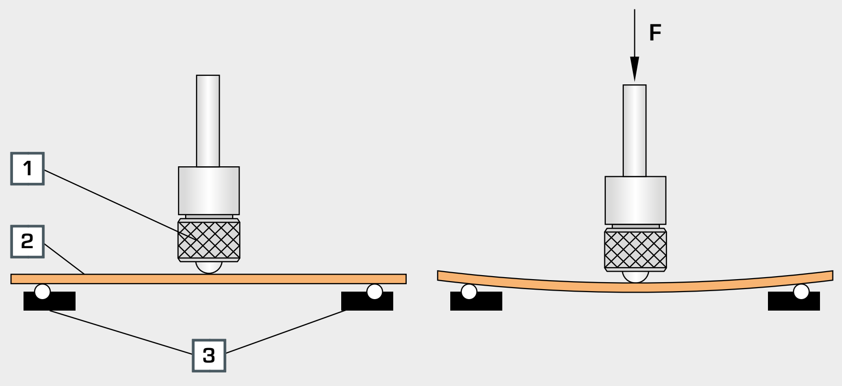
Test process and measurement of the depth of penetration

1 diamond cone, **2** specimen, **I** test pre-load F_0 is applied to the test body and the dial gauge is set to zero, **II** additional test load F_1 is applied for a given duration, **III** additional test load F_1 is removed, **a** depth of penetration due to test pre-load F_0, **b** depth of penetration due to additional test load F_1, **c** elastic recovery after removal of the additional test load F_1, **d** lasting depth of penetration h

Mechanical testing methods

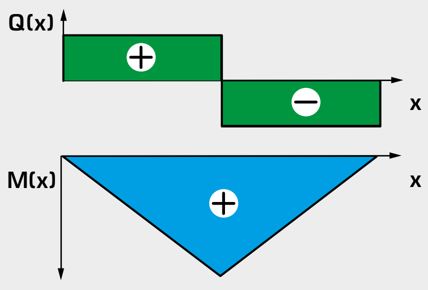
Bending tests for the study of deformation behaviour

The most frequently studied bending load in materials testing is the three-point bending test. Using this method, a beam mounted on two supports is studied under a single force applied to the centre. The bending test demonstrates the relationship between the load of a bending beam and its elastic deformation. The effects of modulus of elasticity and second moment of area are shown.



Test process in the three-point bend test

1 pressure piece, **2** specimen, **3** two supports on which the beam is mounted, **F** test load



Bending stress with profile of shear forces and bending moment

Q shear force, **M** bending moment, **x** distance

Shear test to study the load capacity against shearing

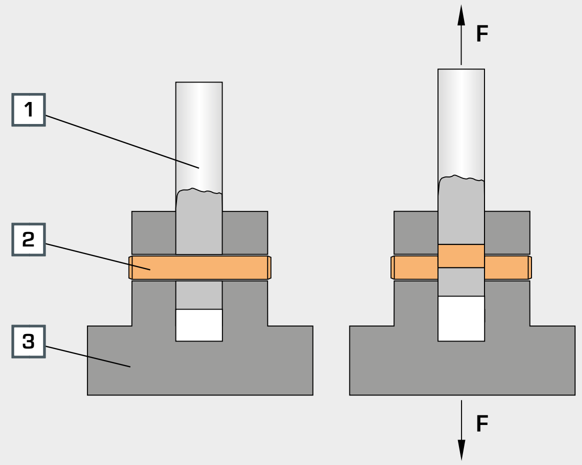
The shear test is applied when testing screws, rivets, pins and parallel keys in order to determine the shear strength of the material or the behaviour of the material under shear strain. To do this, the shear stresses are produced in the specimen by means of external shear forces until the specimen shears off. The resistance of a material against the shear stress can be determined by two different methods, the single-shear and the double-shear testing method.

In the double-shear method, the specimen is sheared off at two cross sections. In the single-shear process, the specimen only shears away at one cross section. Calculating the shear strength in the two processes differs in the cross-sectional area to be applied. The shear strength determined in the shear test is important in the design of bolts, rivets and pins, as well as for calculating the force required for shears and presses.

$$\tau = \frac{F}{2 \cdot A}$$

Shear strength in the double-shear method

τ shear strength, **F** force, **A** shearing surface



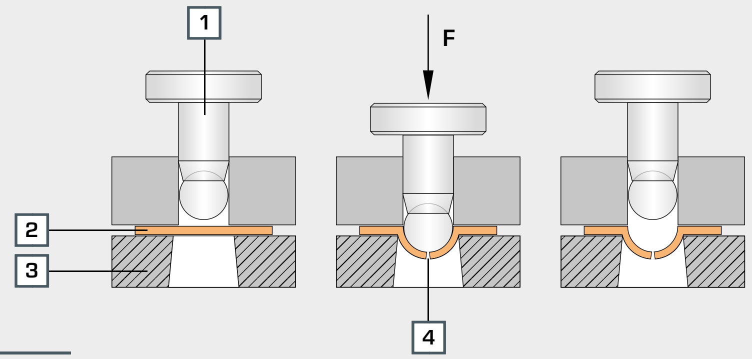
Test process in the double-shear test

1 pull strap, **2** specimen, **3** housing, **F** test load

Cupping test to determine the cupping capacity (cold formability) of sheets and strips

Sheets and strips are subject to high demands in terms of their cold formability for deep drawing. No cracks are allowed to occur when working with these thin sheets. The cupping test checks the cold formability in sheets.

The cupping specimen to be tested is clamped between a blank holder and die and is indented with a hardened spherical stamp (cupped) until the specimen cracks. The depth achieved is considered a standard of comparison for the cold formability. In addition, the type of crack and the surface structure of the sagging area are analysed.



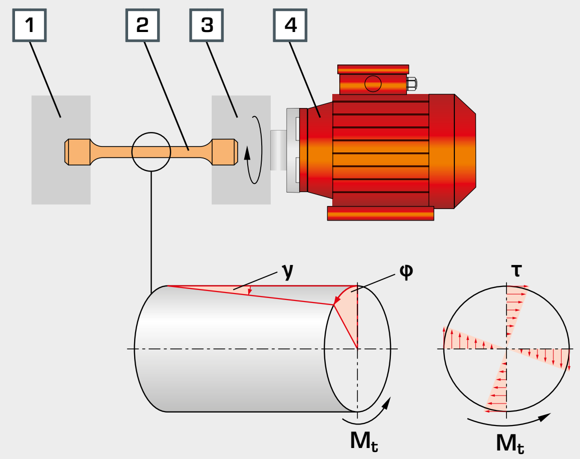
Test process in the cupping test

1 stamp, **2** specimen, **3** die, **4** crack, **F** test load

Torsion test to study the plastic behaviour of materials

Components that are subjected to rotary movements are twisted. This twisting is referred to as torsion. The torsional stiffness determined in the torsion test serves as orientation for the load capacity of the material. This method is applied in shafts, axles, wires and springs and to assess the impact behaviour of tool steels.

In the torsion test, a specimen is clamped at one end and subjected to the load of a steadily increasing moment, known as the twisting moment or torsional moment. The twisting moment causes shear stresses in the cross-section of the specimen and a stress state that leads to deformation and ultimately to fracture.



Test process in the torsion test

1 rigid clamping, **2** specimen, **3** rotating clamping, **4** drive; M_t twisting moment, **γ** shearing angle, **φ** twisting angle, **τ** shear stress

Mechanical testing methods

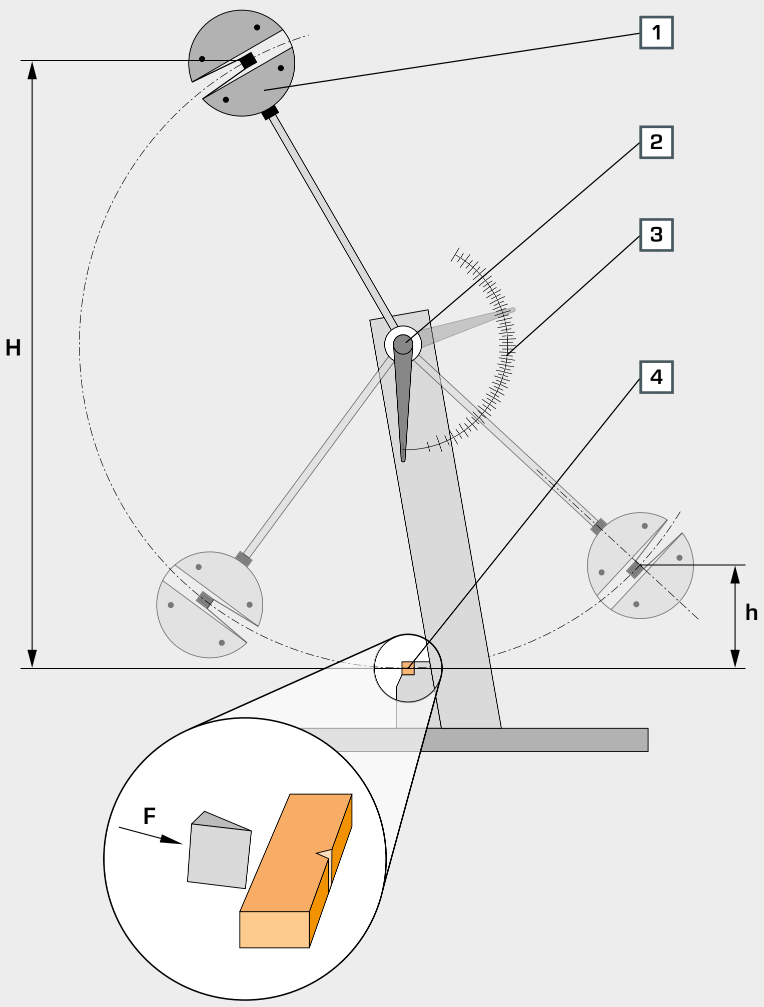
Impact test to determine the toughness property

The impact test is a method with sudden loading and is suitable primarily for determining the cleavage fracture tendency or toughness property of a material. This test method does not provide any values of material characteristics. The determined values of the impact test, the notched-bar impact strength, do not fit directly into calculations on strength. Rather, they help only with a rough selection of materials for a specific task.

The deformation behaviour is often an important criterion for the selection of materials. It can be used to identify quickly which of the selected materials are brittle or tough. The brittleness of the material does not depend on the material alone, but also on other external conditions such as temperature or stress state.

Different testing methods are used to determine the notched-bar impact strength. In the Charpy test, the test body is mounted on two sides and a pendulum strikes the centre of the test body at the height of the notch. In the Izod and Dynstat tests, the test body is upright and a pendulum strikes the free end of the test body above the notch.

Principle of the Charpy notched-bar impact test



1 pendulum hammer, **2** axis of rotation, **3** scale with trailing pointer, **4** notched specimen; **H** height of fall, **h** height of rise, **F** force

In the notched-bar impact test, a pendulum hammer falls down from a maximum height. At its lowest point, the hammer strikes the rear of a notched specimen according to Charpy's principle. If the abutment penetrates or passes through the specimen, the hammer dissipates its impact energy to the specimen. The residual energy of the hammer is reduced when swinging through the lowest possible point (zero point) and the hammer decelerates. When the hammer swings through the zero point, the trailing pointer is dragged along and the applied work for the notched-bar impact is displayed on a scale.

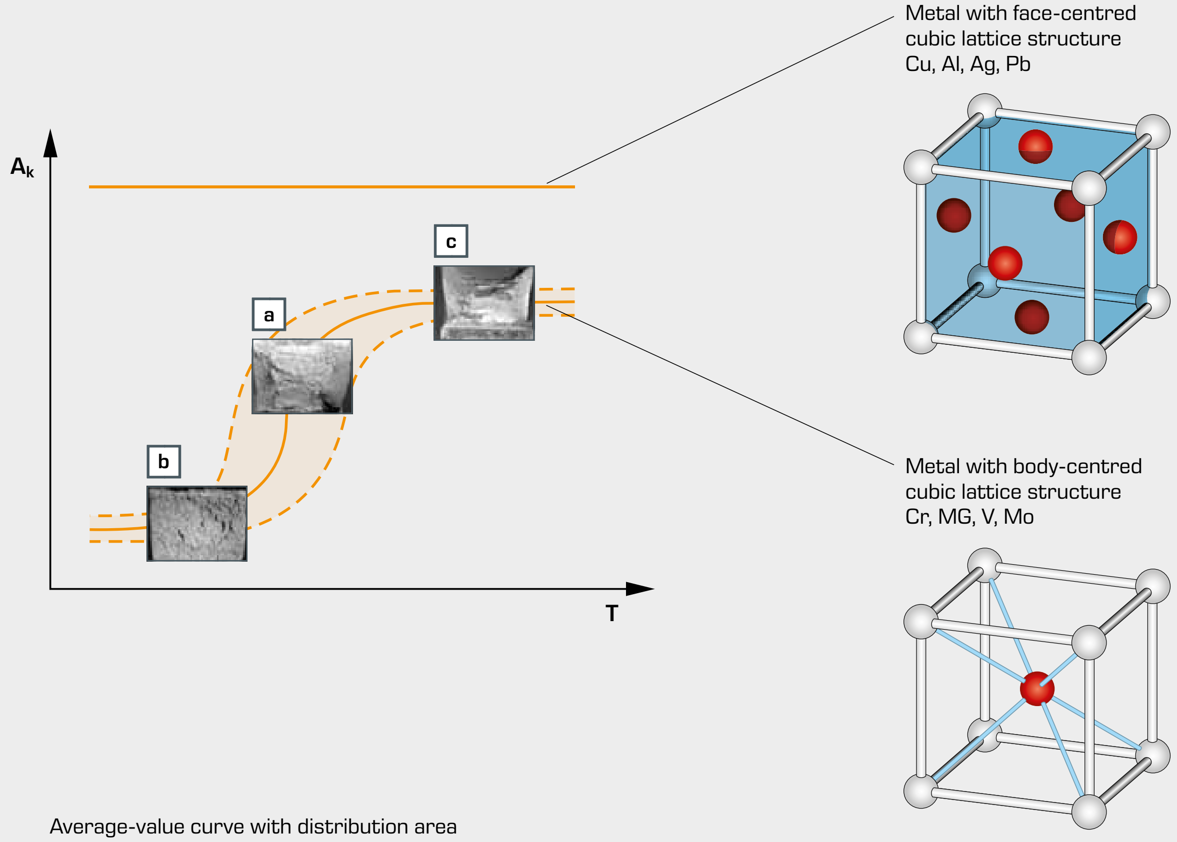
The shape of the notched-bar specimen is standardised.

The necessary notched-bar impact work is the force needed to penetrate a defined notched specimen. The notched-bar impact strength determined from the notched-bar impact work is a measure of the brittleness of the material.

bent specimen

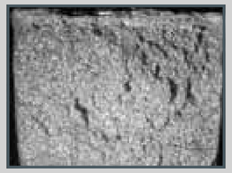
destroyed specimen

Notched-bar impact work-temperature diagram



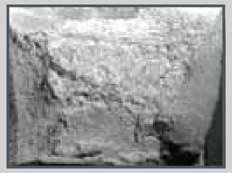
Average-value curve with distribution area

A_k notched-bar impact work, **T** temperature,
a transition region (steep front) with mixed fractures,
b depth position with low-deformation fractures,
c height position with ductile fractures



Low-deformation fracture
(brittle materials)

- material separation by direct stress over cleavage planes
- trans-crystalline fracture
- glossy, practically deformation-free fracture surface



Mixed fracture

- external ductile fracture (microscopic honeycomb fracture), internal low-deformation fracture (microscopic cleavage fracture)

Ductile fracture
(tough materials)

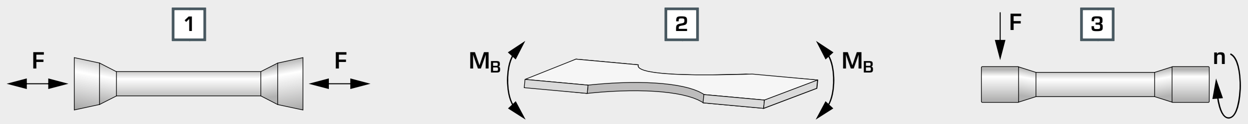
- ductile deformation, fracture due to grains
- matte, heavily deformed fracture surface

Mechanical testing methods

Material fatigue

Fatigue strength test

The fatigue strength defines the load limit up to which a material that is loaded dynamically withstands without breaking. Moving machine parts in particular are subject to dynamic loads, caused by vibrations for example. In this case, a fracture occurs after a high number of load cycles with stresses that are far below the yield point and far below the fracture stress.

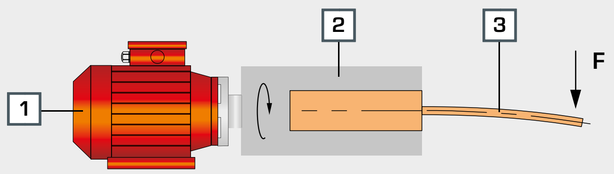


Differently loaded specimens

1 specimen with tensile and compression stress, **2** specimen with stress from alternating bending, **3** specimen with stress from rotary bending; **F** force, $\mathbf{M_B}$ bending moment, **n** speed

Principle of the fatigue strength test with stress on rotary bending

In the fatigue strength test, a rotating, cantilever-mounted specimen is subjected to a bending moment. In the cylindrical specimen, this creates an alternating stress due to rotary bending. After a certain number of load cycles, the specimen fractures because of material fatigue.



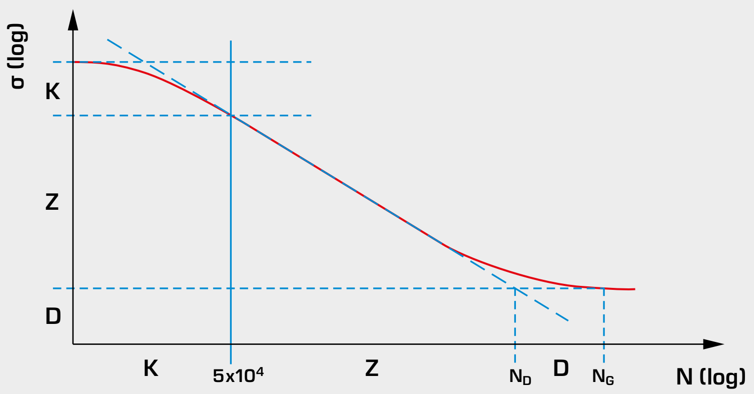
1 drive, **2** rigid clamp, **3** rotating specimen

Analysis of the fracture surface following the fatigue strength test

1 to **3** fatigue fracture, **4** final force fracture

Wöhler diagram for analysis of the experiment

The relationship between load change until fracture and the associated stress load is plotted in a Wöhler diagram.



N load cycles, **σ** stress load, **K** short-term strength, **Z** fatigue strength, **D** endurance strength, $\mathbf{N_D}$ number of load cycles from endurance strength is given, $\mathbf{N_G}$ limit load cycles

The Wöhler diagram contains three regions:

Short-term strength: exceeds a load limit at which the specimen will be damaged in principle

Fatigue strength: with increasing load, there is a decreasing number of load cycles until fracture of the specimen

Endurance strength: maximum stress that a specimen can endure indefinitely and without perceptible deformation, at least up to the number of load cycles $\mathbf{N_G}$

Service life: Number **N** of load cycles until fracture at a certain load

Creep rupture test to study creep

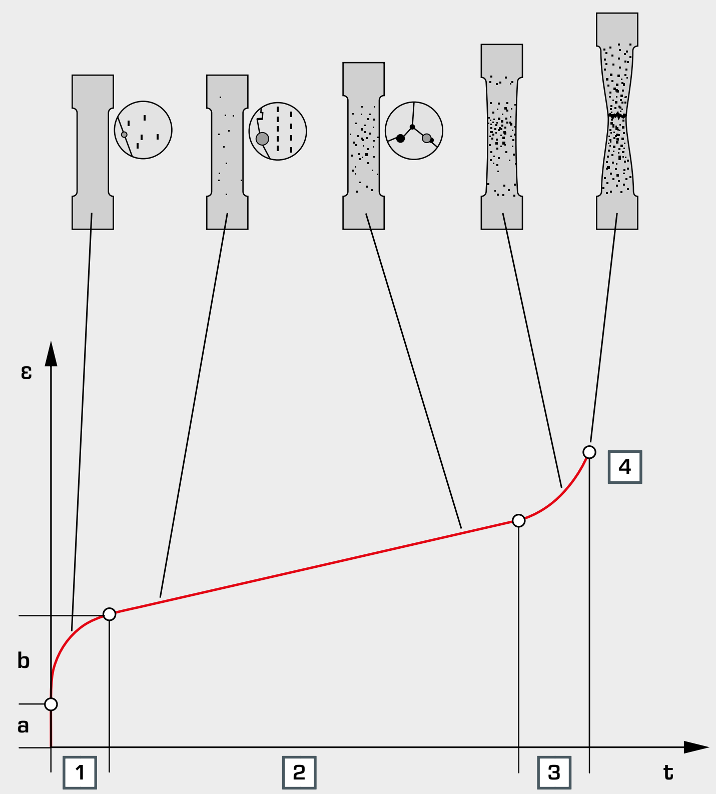
Materials behave differently under lasting static loads at increased temperatures than they do under the same load at room temperature. After a certain amount of time, increased temperatures under stresses below the hot yield point and without an increase in load lead to a slow but steady irreversible plastic deformation, also known as creep. After a sufficiently long, even load time, this leads to fracture of the specimen.

Principle of the creep rupture test

In the creep rupture test, a specimen is subjected to load at constant stress and constant temperature. This experiment is performed multiple times with different stresses, but always at the same temperature. The plastic deformations are measured in continuous intervals. All measured values can then be transferred to a creep diagram. The measured elongation shows a characteristic curve, which is known as the creep curve. The creep rupture test determines the characteristic values for the creep strength and the various strain values.

Creep curve

If the elongation is plotted over time, we get the creep curve.



Change in the specimen over time

t time, **ε** elongation, **1** primary creep, **2** secondary creep, **3** tertiary creep, **4** specimen fracture, **a** elastic deformation, **b** plastic deformation

Creep strength (creep fracture limit / creep strain limit): mechanical stress, which causes permanent elongation or fracture

Strain values: creep, permanent elongation, plastic initial strain, inelastic recovery

In the creep curve we differentiate between three phases in technical creep regions:

Phase 1, the primary creep with decrease of the initially very high creep rate. Here, the influence of the material strength prevails (rapid creep).

Phase 2, the secondary creep with virtually constant creep rate. The dislocation climb when overcoming flow obstacles is located in a steady-state equilibrium.

Phase 3, the tertiary creep with again increasing creep rate until fracture due to increasing necking and increase in the effective stresses. Phase 3 can be very short in the case of low-deformation fractures.