3. MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS

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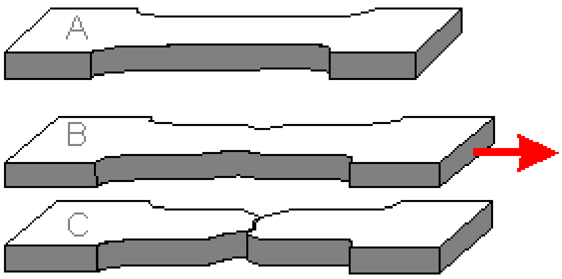
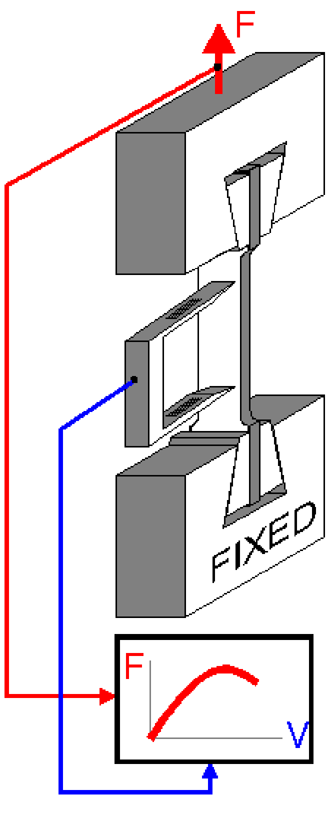
3.1 TENSION TEST

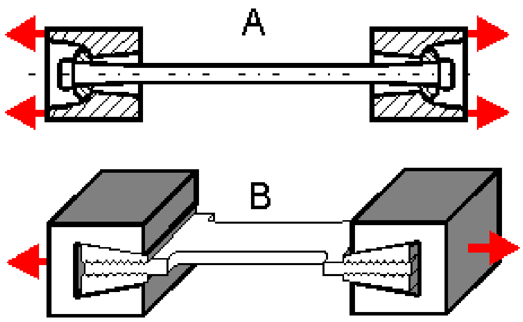
The tension test is the most widely used mechanical test. Principal mechanical properties are obtained from the test. There are a few types of testing specimens including the standard plate and round samples. The specimen (A) is loaded until fracture (C).



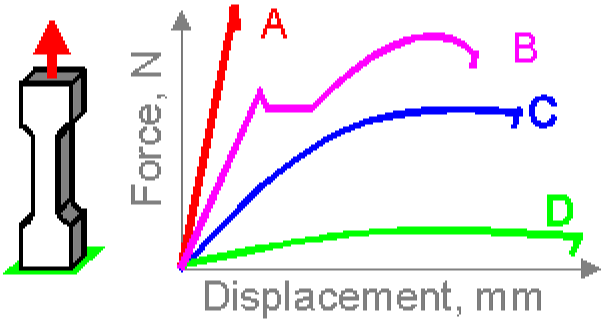
A special device records the applied force and the change in length of the specimen, called the displacement. When the bottom claw is fixed, the upper claw moves with a constant rate until the specimen fractures. To obtain the standard characteristics of the material, the standard geometry of the specimen is used.



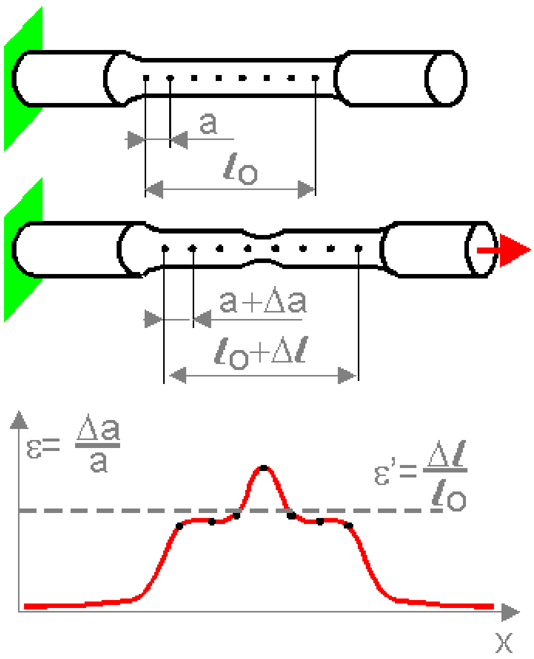
There are round and plate specimens. They have reinforced ends with smooth transitions to the middle. The middle part has a constant cross-sectional area which can be round (A) or rectangular (B).



Structural materials have different relationships between the applied force and displacement of the specimen. Curve A is typical for rigid and high-strength materials such as tool alloys or boron fibers. Curve B is typical for carbon and alloyed steels. Curve C is typical for aluminum and other nonferrous alloys. Curve D is typical for nonmetallic materials such as plastic or rubber.

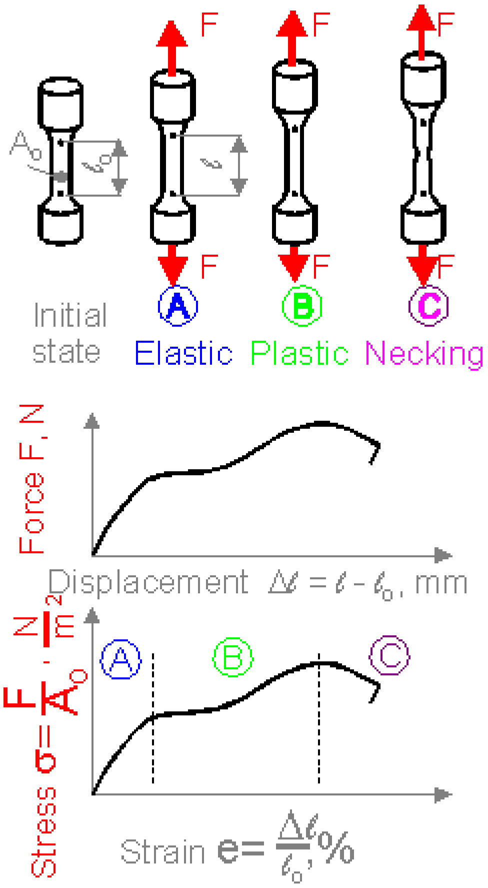


An applied external force F stretches the specimen. There is an average elongation and a local elongation in the specimen. Strain is a measure of the elongation. The tensile strain is defined as the change per unit length due to a force. At the final stage before fracture, plastic deformation concentrates in a section. This effect is called necking. At the point of necking, the local strain is higher than the average one.

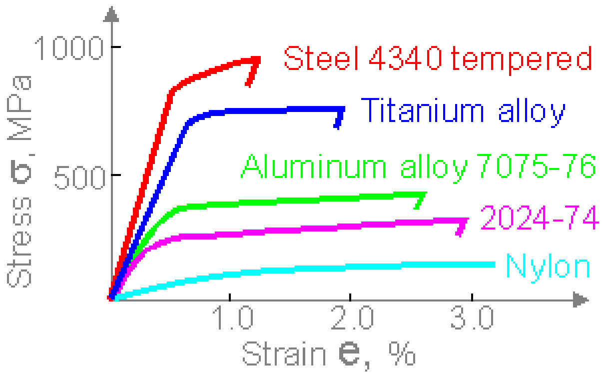


3.2 STRESS - STRAIN DIAGRAM

During the tension test, two main parameters are fixed: force and displacement. These parameters depend on the size of the specimen. To measure the material engineers use stress and strain. Stress is measured in force per unit of area. Strain is the change in length of a fixed uniform bar as compared to its original size. There is elastic deformation at the first stage of loading (A). This type of deformation will be restored when the load is removed. Plastic deformation (B) is not recovered upon load removal. At the final stage of loading, plastic deformation concentrates in a region. This necking (C) is the localized reduction of the cross-sectional area of a specimen.

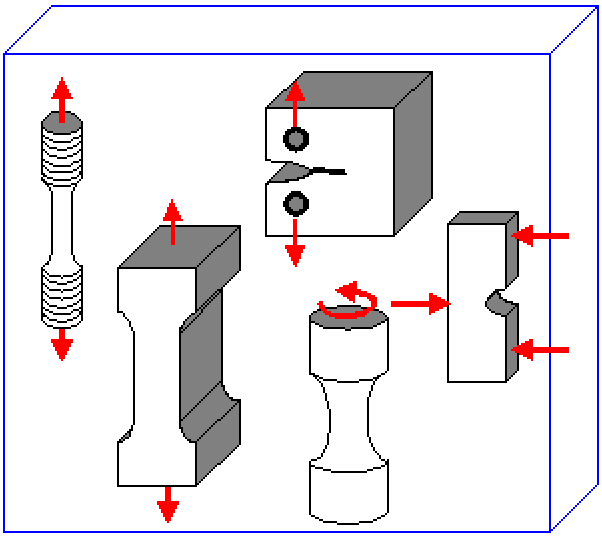


The figure shows typical stress-strain diagrams for different types of material.

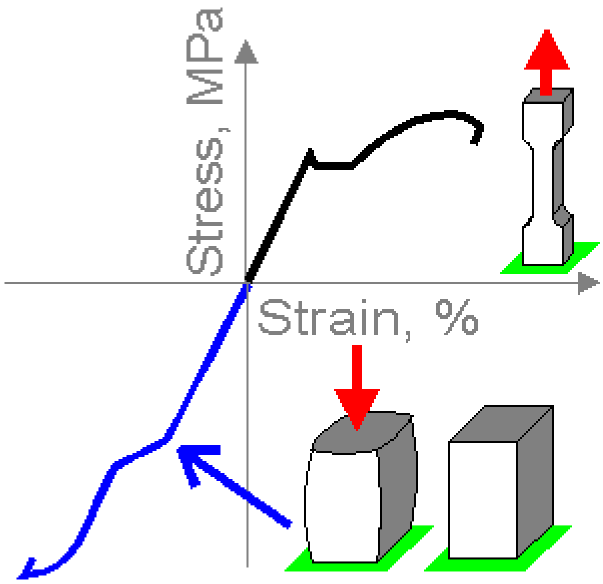


3.3 TESTING SCHEMES

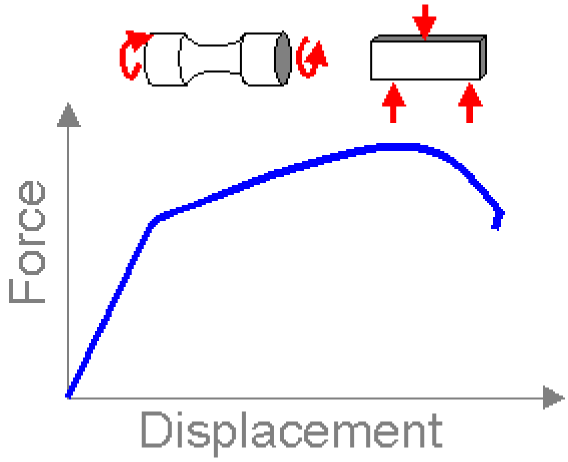
Testing methods depend on the loading scheme of the structure. If a structure is under tension in its most critical parts, then the tension test should be the chosen method to test the material.



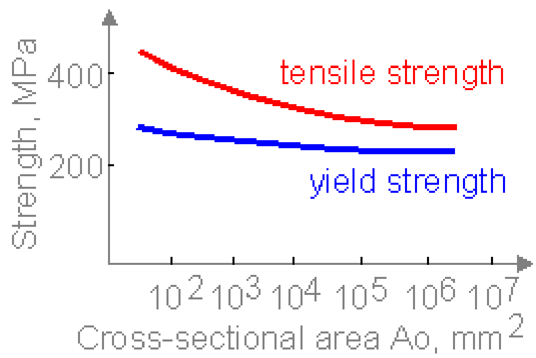
The figure shows typical stress-strain diagrams for tension and compression of low-carbon steel.



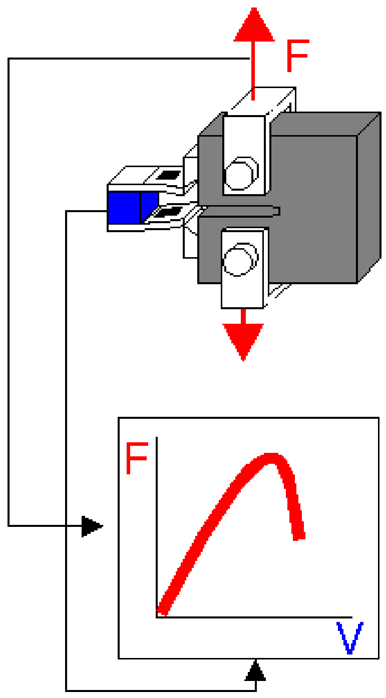
The figure below shows typical diagrams for carbon steel in bending and torsion.



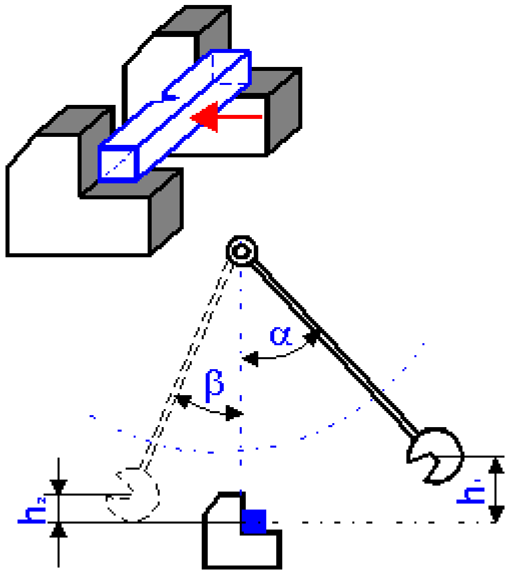
Most of the mechanical characteristics of a material decrease when a larger specimen is used. The figure shows typical characteristics of carbon steel.



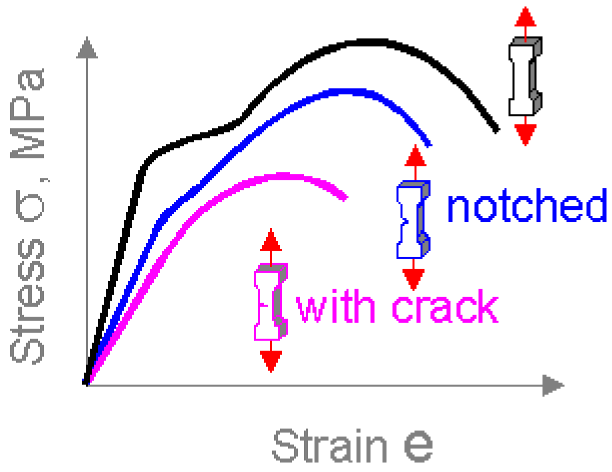
Fracture toughness test (crack resistance) is conducted on specimens with an initial crack. From the diagram of force vs. crack opening displacement, the maximum (critical) value of stress intensity factor is calculated. The "force-displacement" diagram for carbon steel is similar to the three-point bending of an unnotched specimen.



In the Charpy test, a massive element is dropped on a notched specimen. The height from which the element is dropped corresponds to the energy that was used in the fracture process.

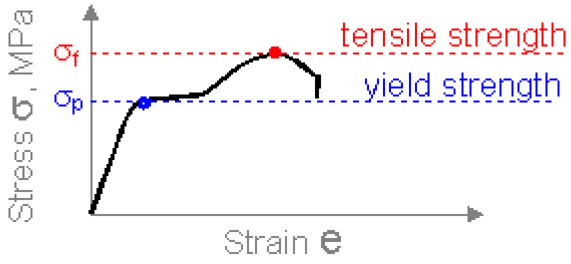


The diagram below depicting stress vs. average strain depends on the presence of notches or cracks in the specimen. Tests with initial cracks are carried out to evaluate crack resistance of the material.

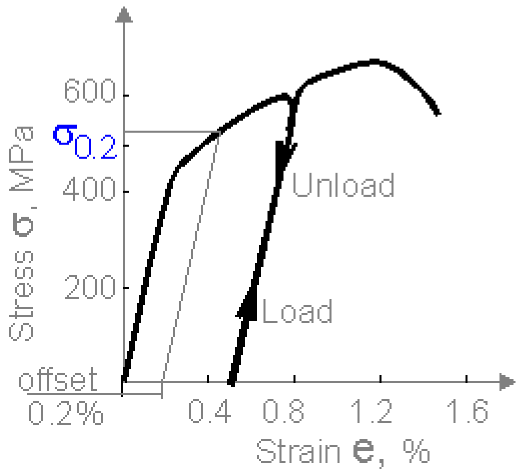


3.4 STRENGTH

There are two important stress parameters in the stress-strain diagrams. Ultimate tensile strength (UTS) in [MPa] or [ksi] is the maximum tensile stress of a material. Yield strength in [MPa] or [ksi] is the stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. UTS is lower than Young's modulus.



Unloading gives unrecovered deformation, called the offset. If the yield point cannot be interpreted from the diagram, the yield strength can be estimated from the offset method with a specified strain of 0.2%. Yield strength defines the stress at which the plastic deformation starts. There are materials that do not have plastic deformation, such as ceramics and diamonds.



Approximate values of the upper limit for the UTS and the yield strength (Y) in decreasing order are the following:

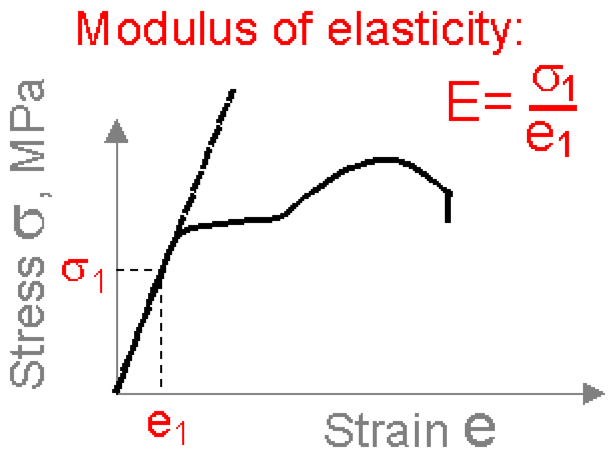
Material	UTS , MPa	Y , MPa
Ceramics	2600	
Molybdenum alloys	2000	1800
Alloy steels	1700	1600
Stainless heat resistant steel	1350	1040
Titanium alloys	1200	1100
Carbon steels	900	400
Copper alloys	750	450
Cast iron	700	550
Aluminum deformed alloys	500	440
Aluminum cast alloys	400	220
Silk	350	
Wood	210	
Human hair	200	
Thermoplastics	80	
Concrete	50	

Approximate values of the strength/density ratio as compared to carbon steel (equals to 1) in decreasing order are the following:

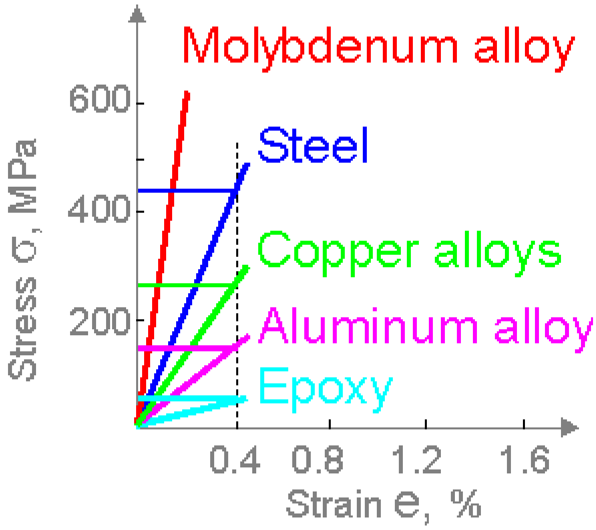
Material	STRENGTH / DENSITY
Silk	8.7
Ceramics	4.5
Human hair	4.3
Wood	2.6
Titanium alloys	2.3
Alloy steels	1.9
Molybdenum alloys	1.7
Aluminum deformed alloys	1.6
Stainless heat resistant steel	1.5
Aluminum cast alloys	1.3
Carbon steels	1
Copper alloys	0.8
Cast iron	0.8
Thermoplastics	0.7
Concrete	0.2

3.5 STIFFNESS

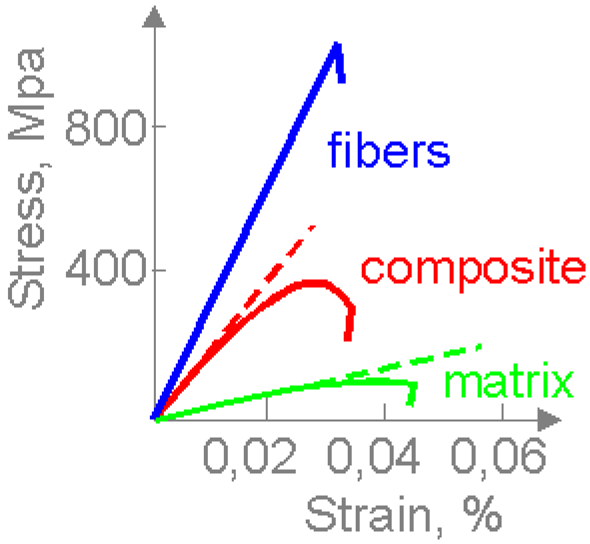
An external force stretches a material. Modulus of elasticity is a measure of the stiffness, defining a material as flexible or relatively rigid. Modulus of elasticity E or Young's modulus in [GPa] or [ksi] is the ratio of stress to corresponding strain below the proportional limit.



The higher the E value, the higher the load required to stretch the specimen to a certain extent.



Composite materials include two or more components with different modulus of elasticity (dashed lines) and deformation diagrams. If the components have the strain-stress curves (blue and green) then the composite diagram has the average modulus of elasticity and is shown between the two curves.

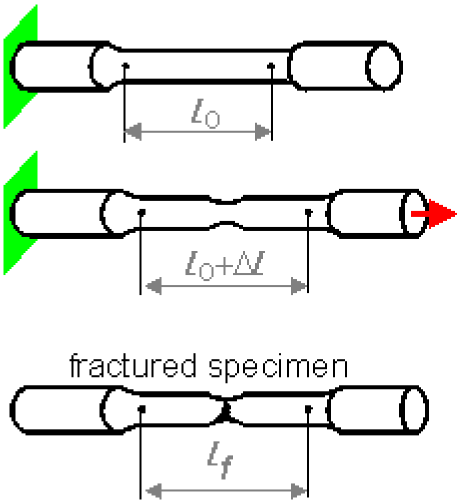


Approximate values of the modulus of elasticity (E) and relative stiffness/density ratio (the ratio is equal to 1 for carbon steel):

Material	E , GPa	STIFFNESS / DENSITY
Boron fibers	400	2.0
Graphite	390	1.95
Molybdenum alloys	325	1.62
Carbon steels	200	1.00
Cast irons	150	0.75
Titanium alloys	110	0.55
Copper alloys	110	0.55
Aluminum alloys	70	0.35
Glass	50	0.2
Concrete	20	0.1
Wood	15	0.08
Epoxies	15	0.075
Lead alloys	14	0.07
Thermoplastics	0.5	0.0025

3.6 DUCTILITY

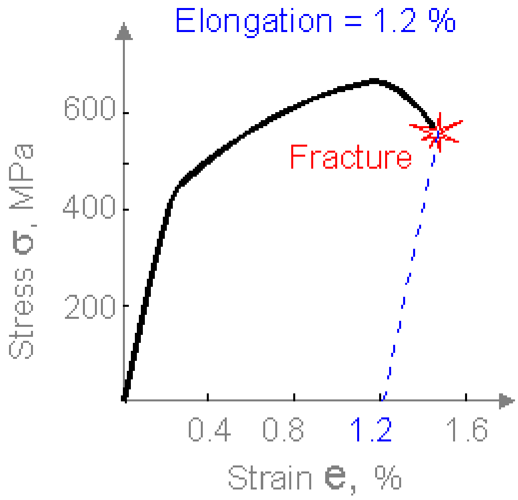
Ductility is an important characteristic of structural materials, corresponding to the ability of a material to deform plastically before full fracture. It helps the material to redistribute high stress from critical parts to neighboring areas. During tension tests, we can observe two common measures of ductility: elongation and reduction of area.



Elongation = (l_f - l_0) / l_0 * 100

Here $\boldsymbol{l_0}$ and $\boldsymbol{l_f}$ are the original and final lengths of the specimen, respectively.

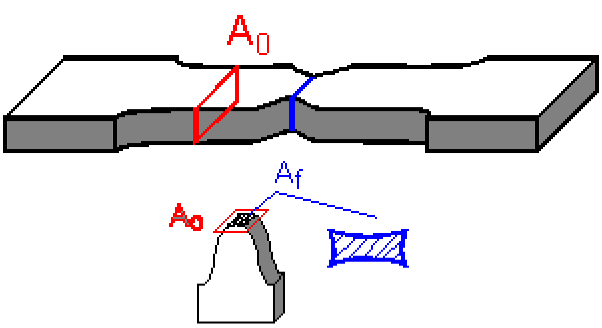
The elongation can be found by stress-strain diagram. It corresponds to maximum strain reduced by elastic recovery.



During the tension test, the specimen becomes narrower. For stainless steel after necking, the cross-sectional area can be two times less than the original area. This is another measure of ductility:

Reduction of area = (A_0 - A_f) / A_0 * 100

Here $\boldsymbol{A_0}$ and $\boldsymbol{A_f}$ are the original and final cross-sectional areas of the specimen at the point of fracture.



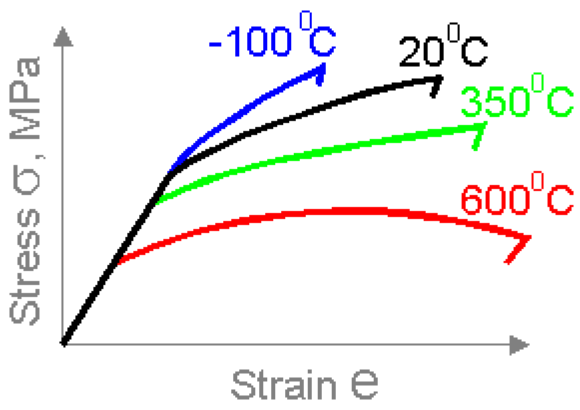
The ductility depends on the structural material, its state (cold-worked), heat-treatment, exploitation temperature and other conditions. Annealing increases the ductility measures.

Approximate maximum values of the elongation in 50mm (El) and the reduction of area (RA):

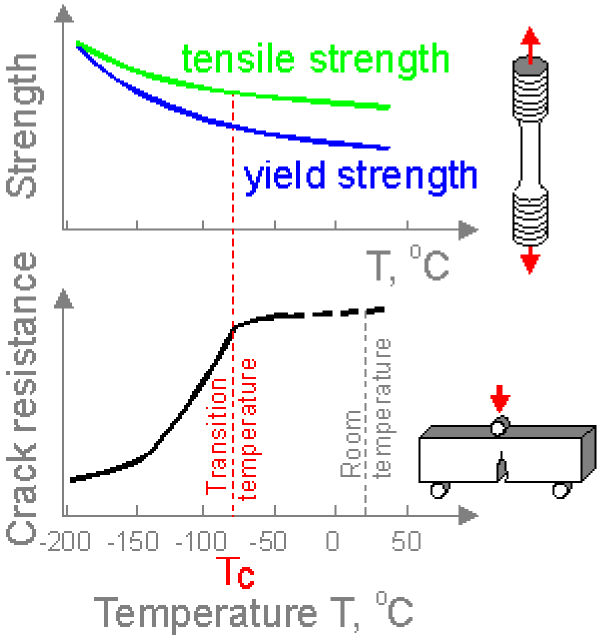
Material	El , %	RA , %
Rubber	700	> 60
Stainless steel 304	58	60
Steel 1020 (as rolled)	36	59
Monel R-405 (hot-rolled)	35	60
Steel 4340 (annealed)	22	49
Titanium alloy R56400	14	30
Ductile cast iron (pearlitic)	2	
Gray cast iron (ferritic)	0.4	

3.7 TEMPERATURE AND DEFORMATION RATE

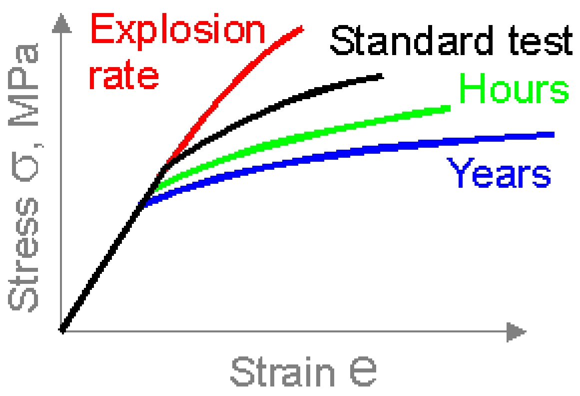
The stress-strain diagram depends on the test temperature. Increasing temperature leads to decreasing tensile strength and yield strength. In this case, the elongation increases. When we reach the melting point all mechanical properties of the solids diminish.



Low temperature decreases the ability of a material to have plastic deformation. The crack resistance characteristics fall dramatically at a certain temperature, known as the transition temperature or critical temperature. This is the temperature of the transition from ductile to brittle fracture. Exploitation of a structure with cracks, high stress concentration and impact loading is prohibited below this temperature.



A test performed over a long time period demonstrates the ability of a material to deform under constant stress. This is the effect of creep. The effect is sufficient when the temperature is high and the nominal stress is bigger than yield strength. We add the additional strains obtained at the creep 10-year test to the standard stress-strain curve. The new curve describes properties of material after 10 years of exploitation. The material is not stronger than in its first days.



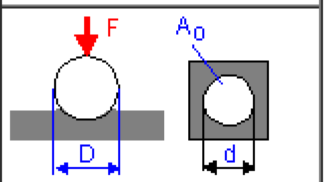
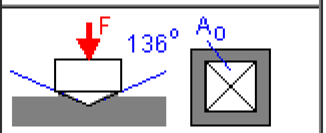
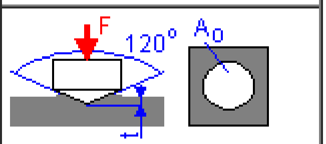
Approximate minimal values of melting point in decreasing order:

Material	Melting point °C
Beryllium	1854
Titanium alloy	1549
Steel	1370
Copper alloy	885
Aluminum alloy	476
Lead	327
Plastics	110

3.8 HARDNESS

Hardness characterizes resistance to permanent indentation and resistance to scratching, and is a commonly used quantity. The test is easily carried out, and does not require specially cut specimens. Hardness also characterizes the resistance of a material to scratching.

Hardness tests:

Test	Indenter	Load, kg	Side view Top view
Brinell	10-mm steel ball, tungsten carbide ball	500 - 3000	
Vickers	Diamond pyramid	1 - 120	
Rockwell	Diamond cone	60 - 150	

The Brinell hardness test is an indentation hardness test, where the indenter is a hard ball. The diameter of the resulting impression is measured. Brinell hardness number HB is the ratio of the applied load to the surface area of the permanent impression made by the ball. The parameter is measured in the same units as stress, but engineers usually write "HB 200."

Vickers hardness test is an indentation hardness test, where the indenter is a square-based pyramidal diamond. The diagonals of the resulting impression are measured. Vickers hardness number HB is the ratio of applied load to the surface area of the permanent impression made by the indenter. The parameter is measured in the same units as stress, but engineers usually write "HV 100."

Rockwell hardness test is an indentation hardness test, where the indenter is a diamond sphero-conical penetrator. The difference in depth of the impression of minor and major loads is measured. Rockwell hardness number HR corresponds to the net increase in the depth of impression.

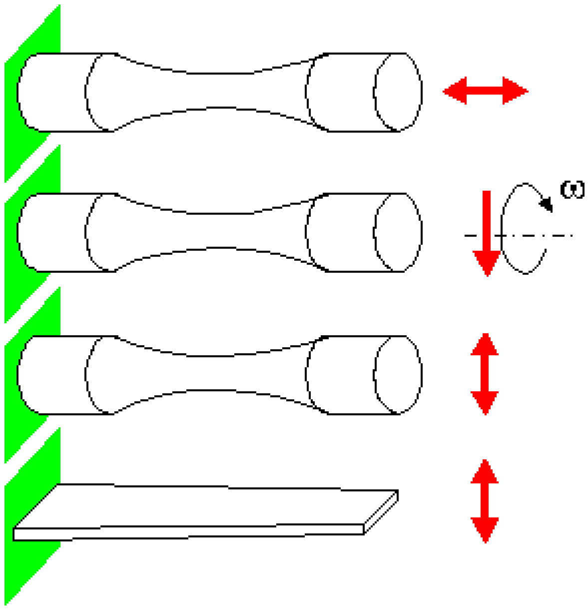
Usually steel is harder than aluminum, and aluminum is harder than lead. Diamond and boron fibers have the highest values of hardness. There is no fundamental correlation between tensile strength of a material and its hardness. Some alloys follow a simple rule: the hardness increases with higher strength (yield strength). Annealing makes the steel softer.

Approximate values of hardness in decreasing order are the following:

Material	HB
Diamond	10000
Boron carbide	4000
Fully hardened tool steel	700
Glass	500
Cold drawn 0.5C steel	350
Titanium	220
Gray iron	200
Annealed mild steel	150
Brass	120
Nickel	90
Gold	40
Silver	25
Pure aluminum	15
Tin	6
Lead	4

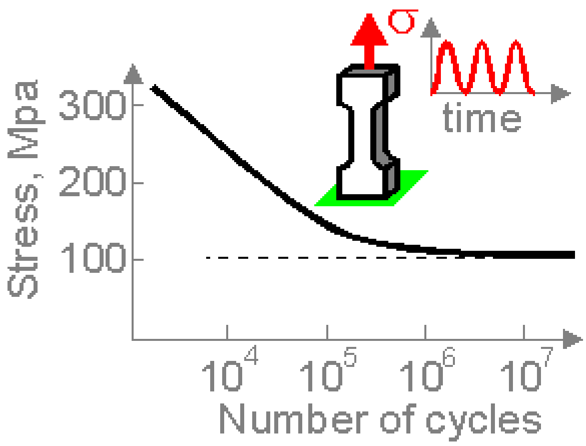
3.9 FATIGUE TESTS

The specimens for fatigue tests have the same geometry as for tension tests or others. Some specimens have regions with small stress concentration. Rigid claws transform tensile and compressive loads. Another type of loading is cyclic bending.

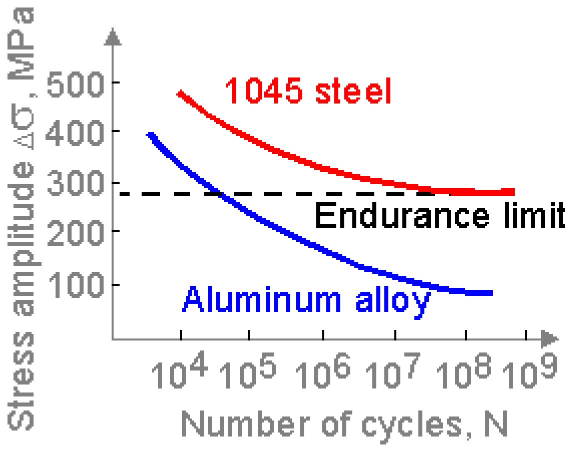


The fatigue life, N_f is the number of cycles of stress or strain that a given specimen can sustain before failure.

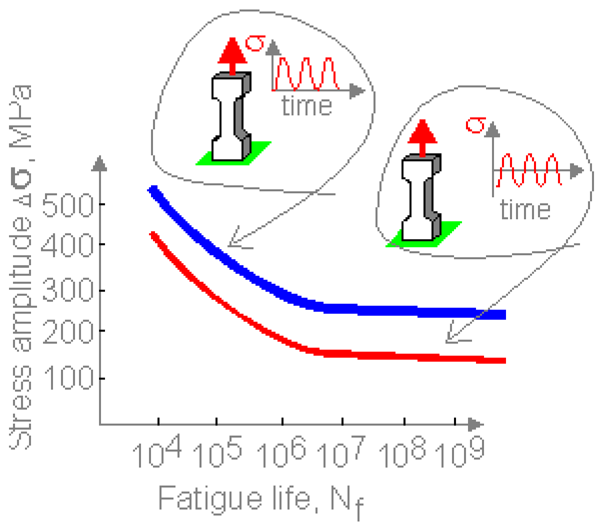
The fatigue tests are carried out at various stress amplitudes to cause total failure of the specimen. The greater the stress amplitude, the fewer cycles the specimen sustains. The most important number is not the maximum value of the stress, but the stress amplitude. Curves "S-N" are used in engineering practice.



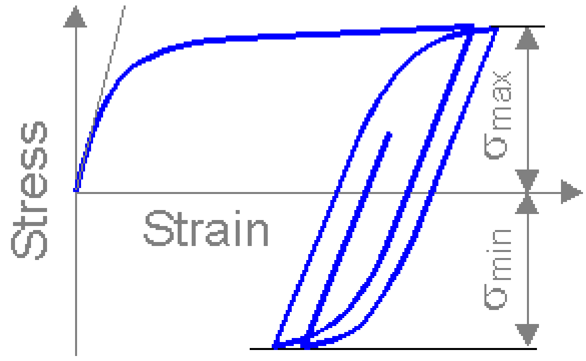
Steels and titanium alloys have an endurance limit. Cyclic loading below the limit does not lead to fracture. Aluminum alloys have no such limit. In some cases the fatigue strength is specified at a fixed number of cycles such as 107. The ratio of the fatigue strength (endurance limit) to yield strength is less than 1.



The type of cyclic loading affects the fatigue life. If stress changes its sign and keeps the amplitude the "S-N" curve lowers.



The main mechanism of fatigue crack initiation and growth is local plastic deformation. There is an accumulation of plastic deformation under cyclic stress that exceeds the yield point.



Approximate values of the ratio of the fatigue strength (FS) to the UTS in decreasing order:

Material	FS / UTS
Titanium	0.6
Steels	0.5
Cast irons	0.42
Copper alloys	0.38
Aluminum alloys	0.2 - 0.5

3.10 SELECTION OF STRUCTURAL MATERIALS

Engineers need to take into account many important properties for material selection. Besides mechanical properties, the cost and technical properties are also important. Stress-strain diagrams are not in demand. The maximum forces, minimum or maximum displacement, number of cycles and lower costs are primary considerations of the structural materials.

Approximate minimum cost per unit volume for wrought materials in comparison with carbon steel:

Material	Relative cost
Silver	600
Molybdenum alloy	200
Nickel	35
Copper alloy	6
Stainless steel	5
Aluminum alloy	2
Carbon steel	1
Plastics	0.2

Condition, shape and size all affect the costs. Usually, cost increases with decreasing thickness or cross section. The price increases exponentially when the strength exceeds 1000 MPa.

The approximate minimum cost of raw materials in comparison with carbon steel bar, hot rolled, round with the same weight:

Fiber
Boron
Kevlar 49
Carbon
Glass E

Relative price of fibers for composite materials in decreasing order:

Material	Relative cost
Carbon steel bars, hot rolled, round	1.0
Carbon steel bars, cold finished, round	1.1
Carbon steel plate and sheet, cold rolled	1.4
Stainless steel sheet, 316	5.5
Stainless steel bars, 303 square	10.2
Aluminum extrusions	4.8
Aluminum sheet, 6061 T6	6.6
Aluminum plate, 2024 T351	9.6
Aluminum bars, rectangular	10.0

Approximate minimum weight of unit volume for structural materials related to the weight of water:

Material	Relative weight
Lead	11.3
Iron	7.9
Nickel	7.8
Copper alloy	7.5
Steel	7.0
Titanium alloy	4.4
Aluminum alloy	2.7
Ceramics	2.3
Beryllium	1.9
Plastics	0.9
Wood	0.4

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