

Toughness is the ability of a material to absorb energy and plastically deform without fracturing. One definition of material toughness is the amount of energy per unit volume that a material can absorb before rupturing. It is also defined as a material's resistance to fracture when stressed.

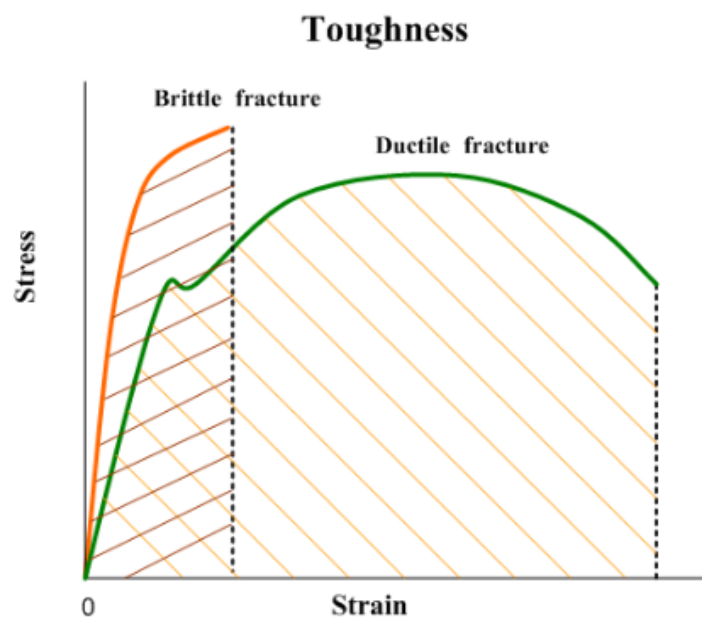
Toughness requires a balance of strength and ductility

Toughness can be determined by integrating the stress-strain curve. It is the energy of mechanical deformation per unit volume prior to fracture. The explicit mathematical description is:

$$\frac{\text{energy}}{\text{volume}} = \int_0^{\epsilon_f} \sigma d\epsilon$$

where

- ϵ is strain
- ϵ_f is the strain upon failure
- σ is stress

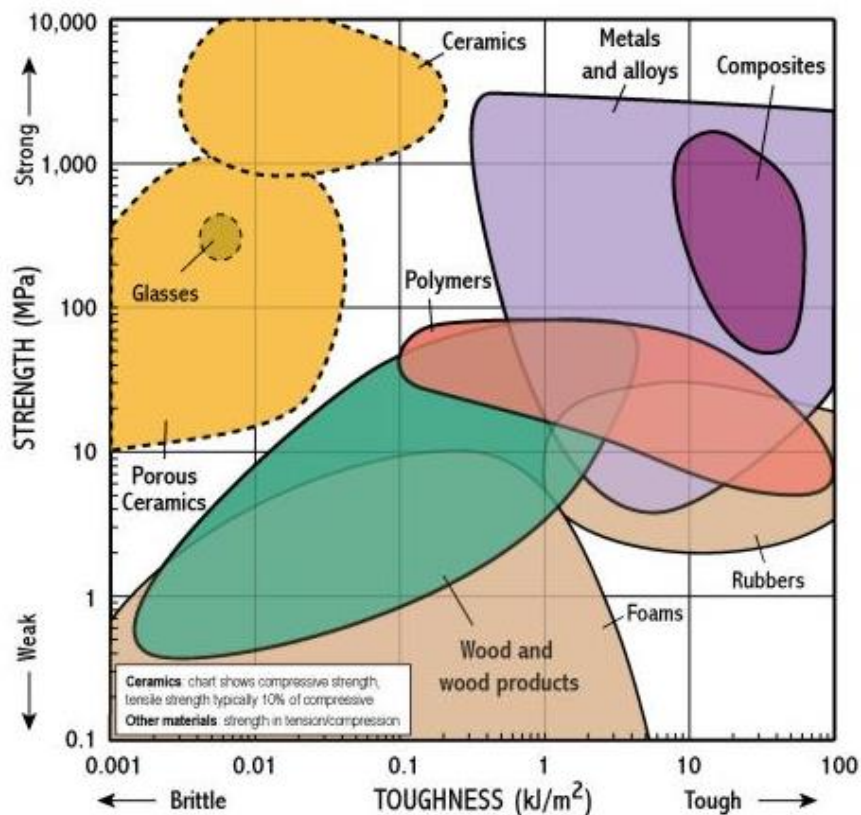


There are several variables that have a profound influence on the toughness of a material. These variables are:

- Strain rate (rate of loading)
- Temperature
- Notch effect

A metal may possess satisfactory toughness under static loads but may fail under dynamic loads or impact. As a rule ductility and, therefore, toughness decrease as the rate of loading increases. Temperature is the second variable to have a major influence on its toughness. As temperature is lowered, the ductility and toughness also decrease. The third variable is termed notch effect, has to do with the distribution of stress.

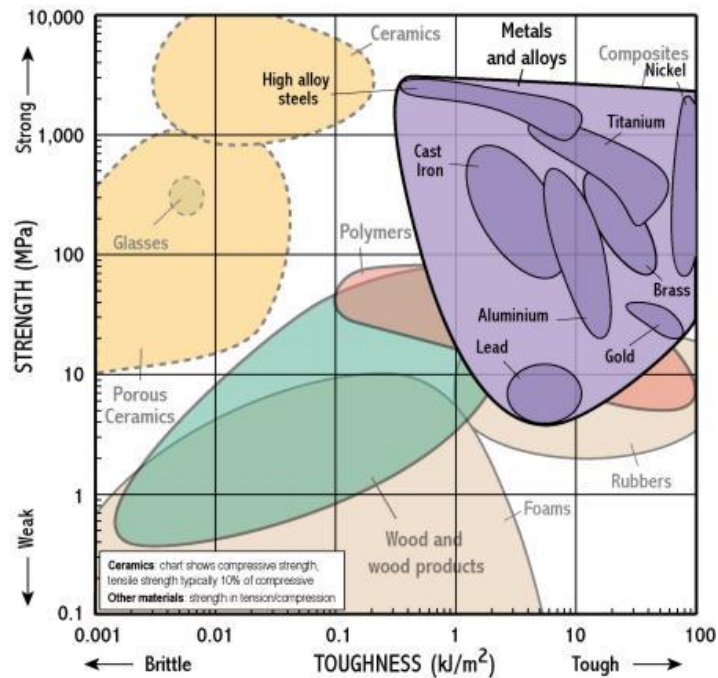
Relation between Strength and toughness



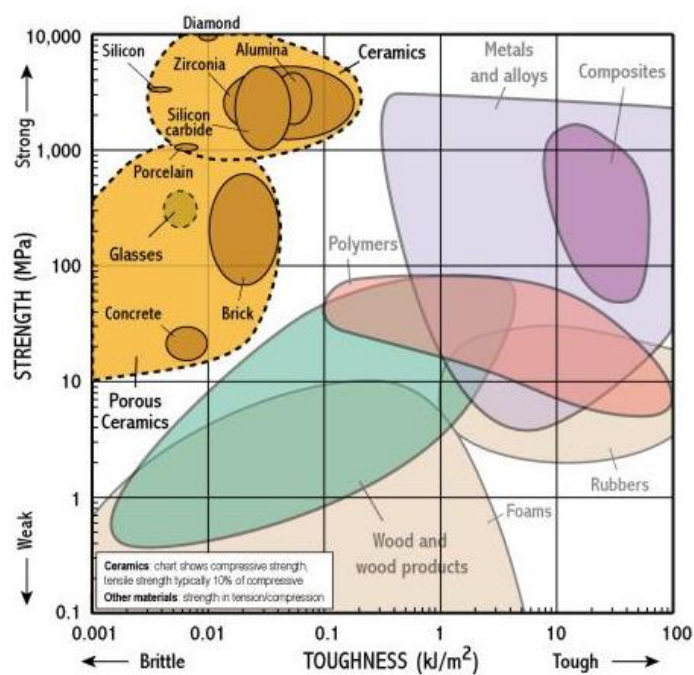
◆ Metals and alloys

Example Uses

- Steel is often used to absorb energy in car impacts because it is tough and strong
- Saw blades and hammer heads are quenched and tempered steel to get moderately high strength with good toughness



◆ Ceramics and building materials



General Information

- Strength measures the resistance of a material to failure, given by the applied stress (or load per unit area)
- The chart shows yield strength in tension for all materials, except for ceramics for which compressive strength is shown (their tensile strength being much lower)
- Toughness measures the energy required to crack a material; it is important for things which suffer impact
- There are many cases where strength is no good without toughness, e.g. a car engine, a hammer
- Increasing strength usually leads to decreased toughness
- Tempered steel is tougher but less strong than after quenching.

There are several standard types of toughness test that generate data for specific loading conditions and/or component design approaches. Two of the toughness properties that will be discussed in more detail are:

- 1) impact toughness,
- 2) fracture toughness.

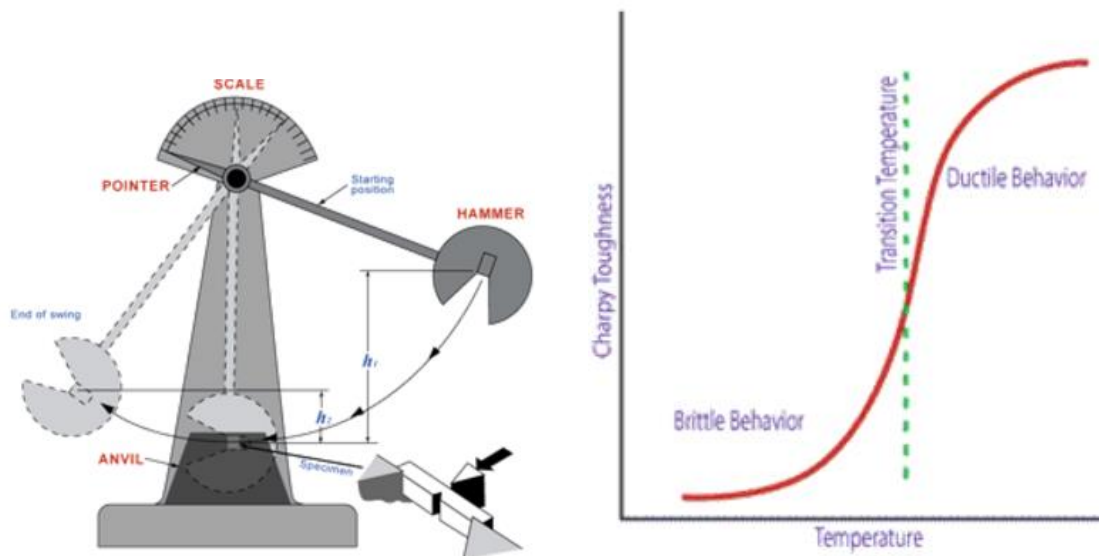
The impact toughness (Impact strength) of a material can be determined with a Charpy or Izod test. These tests are named after their inventors and were developed in the early 1900's before fracture mechanics theory was available. Impact properties are not directly used in fracture mechanics calculations, but the economical impact tests continue to be used as a quality control method to assess notch sensitivity and for comparing the relative toughness of engineering materials.

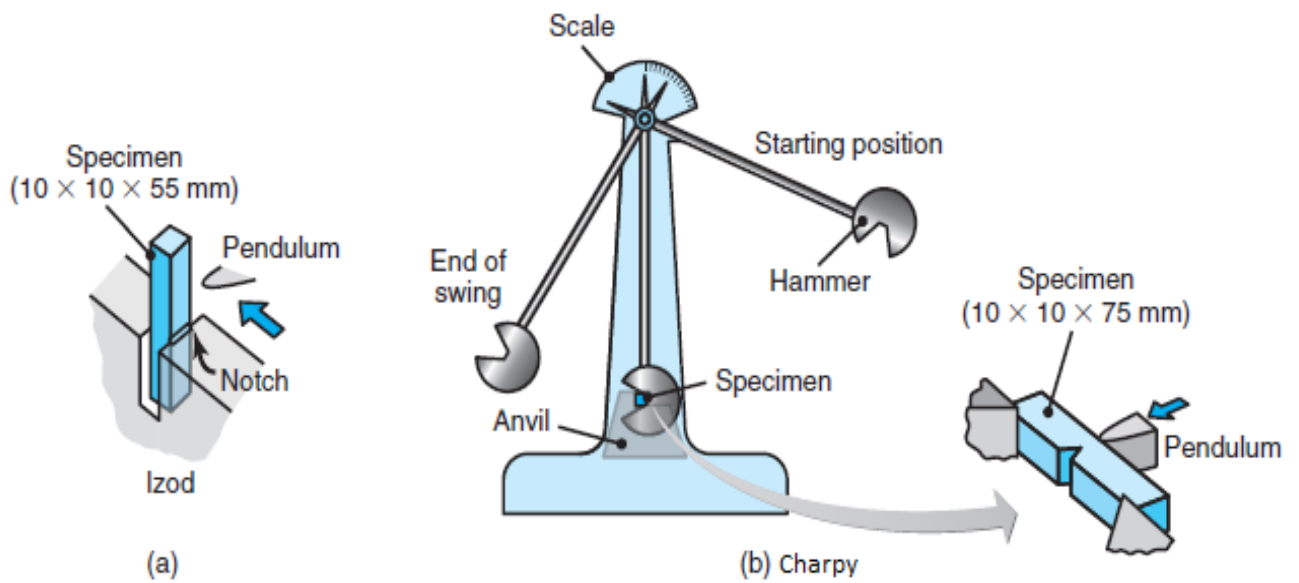
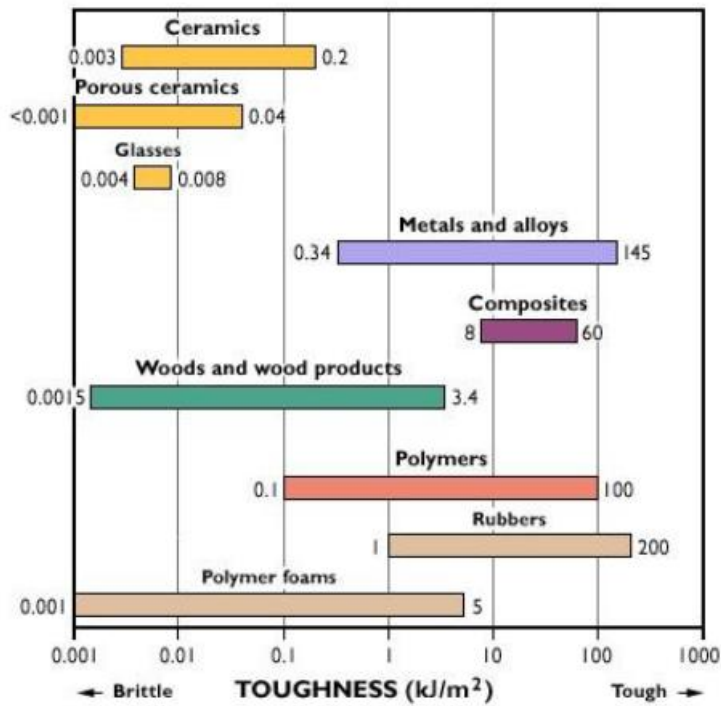
The two tests use different specimens and methods of holding the specimens, but both tests make use of a pendulum-testing machine. The impact toughness of a metal is determined by measuring the energy absorbed in the fracture of the specimen. This is simply obtained by

noting the height at which the pendulum is released and the height to which the pendulum swings after it has struck the specimen. The height of the pendulum times the weight of the pendulum produces the potential energy and the difference in potential energy of the pendulum at the start and the end of the test is equal to the absorbed energy.

Since toughness is greatly affected by temperature, a Charpy or Izod test is often repeated numerous times with each specimen tested at a different temperature. It can be seen that at low temperatures the material is more brittle and impact toughness is low. At high temperatures the material is more ductile and impact toughness is higher. The transition temperature is the boundary between brittle and ductile behavior and this temperature is often an extremely important consideration in the selection of a material.

The testing according different standards such as : According to [ASTM](#) A370 or ISO 148 for Charpy test and ASTM D256 for Izod .





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Izod vs Charpy

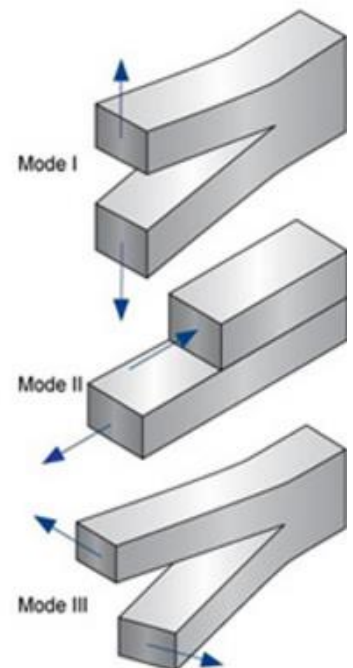
Fracture toughness is an indication of the amount of stress required to propagate a preexisting flaw. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size will be present in some number of components and use the linear elastic fracture mechanics (LEFM) approach to design critical components. A parameter called the stress-intensity factor (K) is used to determine the fracture toughness of most materials.

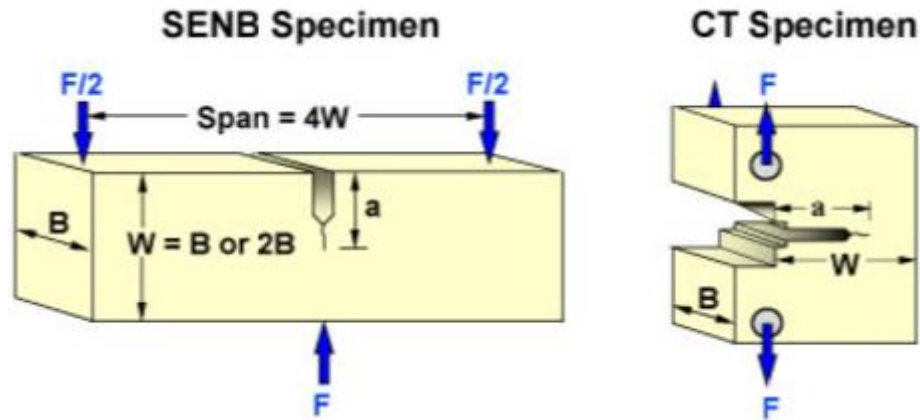
The fracture toughness (K_{IC}) is the critical value of the stress intensity factor at a crack tip needed to produce catastrophic failure under simple uniaxial loading. The subscript I stands for Mode I loading (uniaxial), illustrated in figure a while the subscript C stands for critical. The fracture toughness is given by:

$$K_{IC} = Y\sigma_c\sqrt{\pi a}$$

Where (Y) is a dimensionless geometry factor on the order of 1, (σ_c) is the stress applied at failure, and (a) is the length of a surface crack (or one-half the length of an internal crack).

(KIC) are $\text{MPa}\cdot\text{m}^{1/2}$.





which provides values for K_{IC} under “plane strain” conditions, meaning that (Note $B=t$ = thickness) :

$$t \geq 2.5 \left(K_{IC} / \sigma_y \right)^2$$

, where t is the sample thickness.

Material	Yield Strength		K_{IC}	
	MPa	ksi	MPa \sqrt{m}	ksi $\sqrt{in.}$
Metals				
Aluminum alloy ^a (7075-T651)	495	72	24	22
Aluminum alloy ^a (2024-T3)	345	50	44	40
Titanium alloy ^a (Ti-6Al-4V)	910	132	55	50
Alloy steel ^a (4340 tempered @ 260°C)	1640	238	50.0	45.8
Alloy steel ^a (4340 tempered @ 425°C)	1420	206	87.4	80.0
Ceramics				
Concrete	—	—	0.2–1.4	0.18–1.27
Soda-lime glass	—	—	0.7–0.8	0.64–0.73
Aluminum oxide	—	—	2.7–5.0	2.5–4.6
Polymers				
Polystyrene (PS)	25.0–69.0	3.63–10.0	0.7–1.1	0.64–1.0
Poly(methyl methacrylate) (PMMA)	53.8–73.1	7.8–10.6	0.7–1.6	0.64–1.5
Polycarbonate (PC)	62.1	9.0	2.2	2.0

Example: Estimate the flaw size responsible for the failure of a turbine motor made from partially stabilized Aluminum oxide that fractures at a stress level of 300 MPa .

Solution :

From above, we know that:

$$K_{IC} = Y\sigma_f\sqrt{\pi a}$$

Rearranging:

$$a_c = \frac{1}{\pi} \left(\frac{K_{IC}}{\sigma} \right)^2$$

From table, $K_{IC} = 2.7 \text{ MPa.m}^{1/2}$

Continue -..... etc.

Viscoelastic materials

Almost, all materials possess viscoelastic properties, and operate differently in tensile and compression strength and loading styles. Viscoelasticity in polymer is more sensible than metals. That is, deformation in polymer is not only a function of applied load, but it also depends on time (loading rate). The materials which their deformation depends on time, as viscoelastic materials, have both solid and fluid like behaviors. Linear viscoelasticity is often used successfully for describing the real behavior in case of small or moderate loads. The use of thermoplastics in structural applications demands accurate design data that spans appropriate ranges of stress, strain rate, time and temperature.

In polymeric materials, the primary molecular chains are held together by weak cohesive forces. These chains are constantly rearranging their configurations by random thermal motion. The driving force for these motions is the thermal energy contained in the system. When subjected to an external stress, rearrangement on a local scale takes place rapidly but that on a larger scale occur rather slowly. This in turn leads to a wide range of time spans where changes in mechanical properties are observed. This behavior is termed viscoelasticity. The amount of crystallinity, cross-linking and chain structure also affects the overall behavior. Using polymer, instead of metal, is increasingly being developed. The vast differences between polymer and metal properties and some disadvantages like polymer's higher viscoelasticity than metal, which results in creep and relaxation behavior in polymer, its very lower elasticity modulus and low fracture stress than metal, high thermal expansion coefficient (which is 10 times more than metals), low dimensional stability.

Viscoelasticity is the study of materials which exhibit features of both elastic and viscous behavior. Elastic materials deform instantaneously when a load is

applied, and remembers its original conformation, returning there instantaneously when the load is removed. A mechanical model representing this can be seen by observing a spring.

On the other hand, viscous materials do not show such behavior, instead they exhibit time dependent behavior. While under stress, a viscous body strains at a constant rate, and when its load is removed, the material fails to return to its initial conformation. A mechanical model of a viscous material can be seen by observing a dash-pot. Viscoelastic materials exhibit the combined characteristics of both elastic and viscous behavior, resulting in partial recovery. A mechanical model of viscoelastic behavior can be represented by various combinations of spring and dash-pot elements in series or parallel. Figure shows the standard viscoelastic response of polymers undergoing creep and stress relaxation. By analyzing the creep modulus and relaxation modulus, further insight may be gained regarding the viscoelastic behavior of polymers.

The Creep behavior of viscoelastic materials

The creep phenomena is defined as a slow continuous deformation over time at constant load. Creep is an important consideration in the design. However, the processes of creep can be subdivided and examined into the three categories primary creep, tertiary creep and steady state creep. The processes are illustrated in figure and are explained below:

1.Primary creep

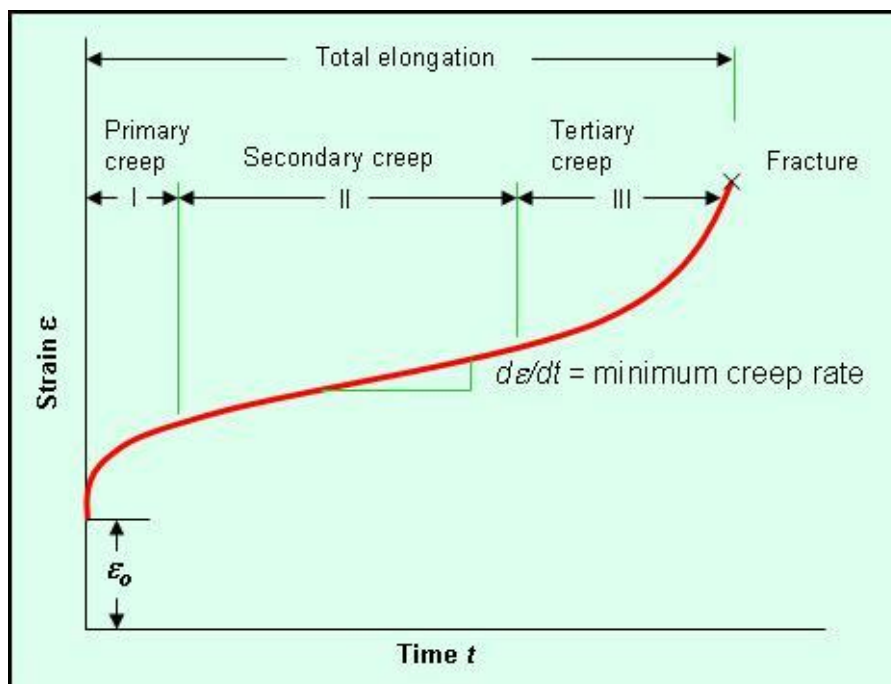
During primary creep, the strain rate decreases with time until a constant rate is reached. And this tends to occur over a short period. Primary creep strain is usually less than one percent of the sum of the elastic, steady state, and primary strains. The mechanism in the primary region is the climb of dislocations that are not pinned in the matrix.

2. Steady state creep

Steady- state creep is so named because the strain rate is constant. In this region, the rate of strain hardening by dislocations is balanced by the rate of recovery. Steady-state creep is roughly centered at the minimum in the plot of creep rate versus time.

3. Tertiary creep

In the tertiary region, the high strains start to cause necking of the material just as in the tensile test. This necking causes an increase in the local stress of the component, which further accelerates the strain.



The steady-state creep rate is strongly affected by temperature, as shown by equation:

$$\dot{\epsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

Where :

$\dot{\epsilon}_s$ steady state creep rate (h^{-1})

K_2 constant of creep equation

Q_c activation energy for creep (kJ/mol)

R constant 8.3144 J/(mol.K)

σ stress (MPa)

T temperature (K)

Example

Steady-state creep data for an alloy at 200°C yield:

$\dot{\epsilon}_s$ (hr^{-1})	σ (MPa)
2.5×10^{-3}	55
2.4×10^{-2}	69

The activation energy for creep is known to be 140 kJ/mol. What is the steady-state creep rate at 250°C and 48 MPa?

Sol :

$$\dot{\epsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

$$\ln \dot{\epsilon}_{s1} = \ln K_2 + n \ln \sigma_1 - \frac{Q_c}{RT_1}$$

$$\ln \dot{\epsilon}_{s2} = \ln K_2 + n \ln \sigma_2 - \frac{Q_c}{RT_2}$$

Now we can subtract these to yield:

$$\ln\left(\frac{\dot{\epsilon}_{s1}}{\dot{\epsilon}_{s2}}\right) = n \ln\left(\frac{\sigma_1}{\sigma_2}\right)$$

Notice that because $T_1 = T_2$, the last term cancels out. Substituting in the data that was given:

$$\ln\left(\frac{2.4 \times 10^{-2}}{2.5 \times 10^{-3}}\right) = n \ln\left(\frac{69}{55}\right)$$

$$n = 9.97$$

$$K_2 = 3.27 \times 10^{-5} \quad (\text{h}^{-1})$$

$$\dot{\epsilon}_s = (3.27 \times 10^{-5} \text{ hr}^{-1})(48 \text{ MPa})^{9.97} \exp\left[-\frac{(140,000 \text{ J / mole})}{(8.314 \text{ J / mole} - ^\circ\text{K})(523^\circ\text{K})}\right]$$

$$\dot{\epsilon}_s = 1.97 \times 10^{-2} \text{ hr}^{-1}$$

Relation between materials and activation energy

Metal	Q_0 for creep kJ mole^{-1}
Aluminium	140
Copper	197
α -Iron	305
γ -Iron	297
Magnesium	117
Zinc	88

Relation between materials and Creep

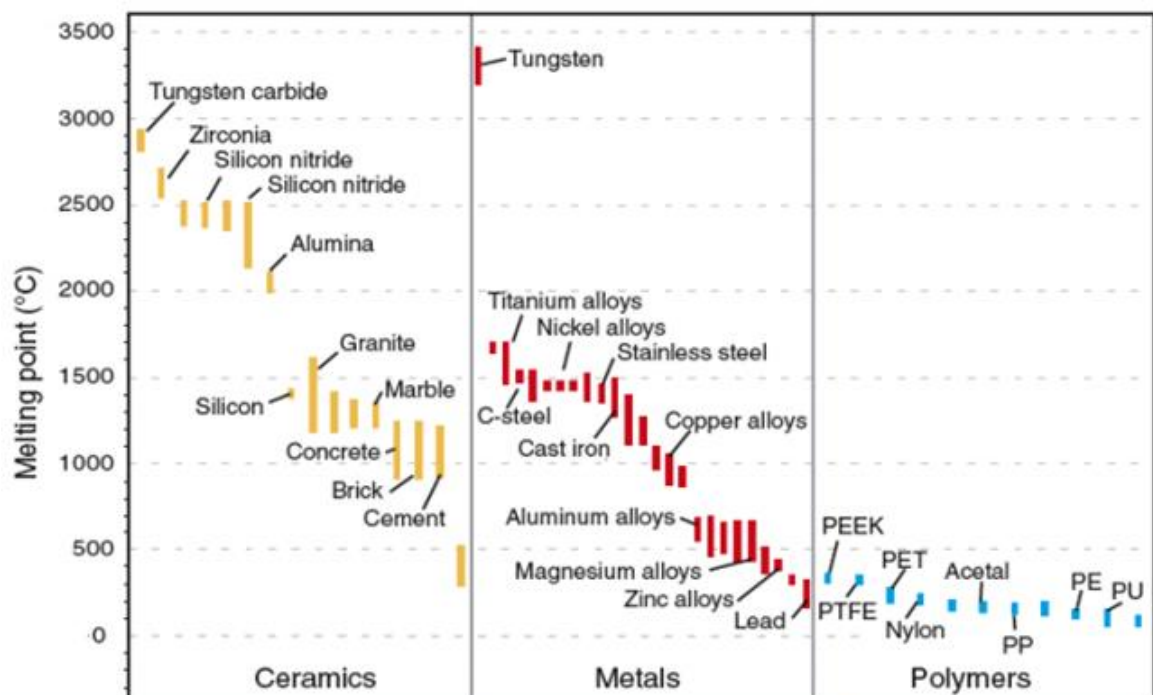
The temperature at which materials start to creep depends on their melting point. As a general rule, it is found that creep starts when

$$T > 0.3 \text{ to } 0.4 T_M \text{ for metals,}$$
$$T > 0.4 \text{ to } 0.5 T_M \text{ for ceramics,}$$

where T_M is the melting temperature in kelvin. However, special alloying procedures can raise the temperature at which creep becomes a problem. Polymers, too, creep — many of them do so at room temperature.

Melting or softening^(S) temperature

Material	T(K)	Material	T(K)
Diamond, graphite	4000	Gold	1336
Tungsten alloys	3500–3683	Silver	1234
Tantalum alloys	2950–3269	Silica glass	1100 ^(S)
Silicon carbide, SiC	3110	Aluminum alloys	750–933
Magnesia, MgO	3073	Magnesium alloys	730–923
Molybdenum alloys	2750–2890	Soda glass	700–900 ^(S)
Niobium alloys	2650–2741	Zinc alloys	620–692
Beryllia, BeO	2700	Polyimides	580–630 ^(S)
Iridium	2682–2684	Lead alloys	450–601
Alumina, Al ₂ O ₃	2323	Tin alloys	400–504
Silicon nitride, Si ₃ N ₄	2173	Melamines	400–480 ^(S)
Chromium	2148	Polyesters	450–480 ^(S)
Zirconium alloys	2050–2125	Polycarbonates	400 ^(S)
Platinum	2042	Polyethylene, high-density	300 ^(S)
Titanium alloys	1770–1935	Polyethylene, low-density	360 ^(S)
Iron	1809	Foamed plastics, rigid	300–380 ^(S)
Carbon steels	1570–1800	Epoxy, general purpose	340–380 ^(S)
Cobalt alloys	1650–1768	Polystyrenes	370–380 ^(S)
Nickel alloys	1550–1726	Nylons	340–380 ^(S)
Cermets	1700	Polyurethane	365 ^(S)
Stainless steels	1660–1690	Acrylic	350 ^(S)
Silicon	1683	GFRP	340 ^(S)
Alkali halides	800–1600	CFRP	340 ^(S)
Beryllium alloys	1540–1551	Polypropylene	330 ^(S)
Uranium	1405	Ice	273
Copper alloys	1120–1356	Mercury	235



The **Larson-Miller parameter** is a means of predicting the lifetime of material vs. time and temperature

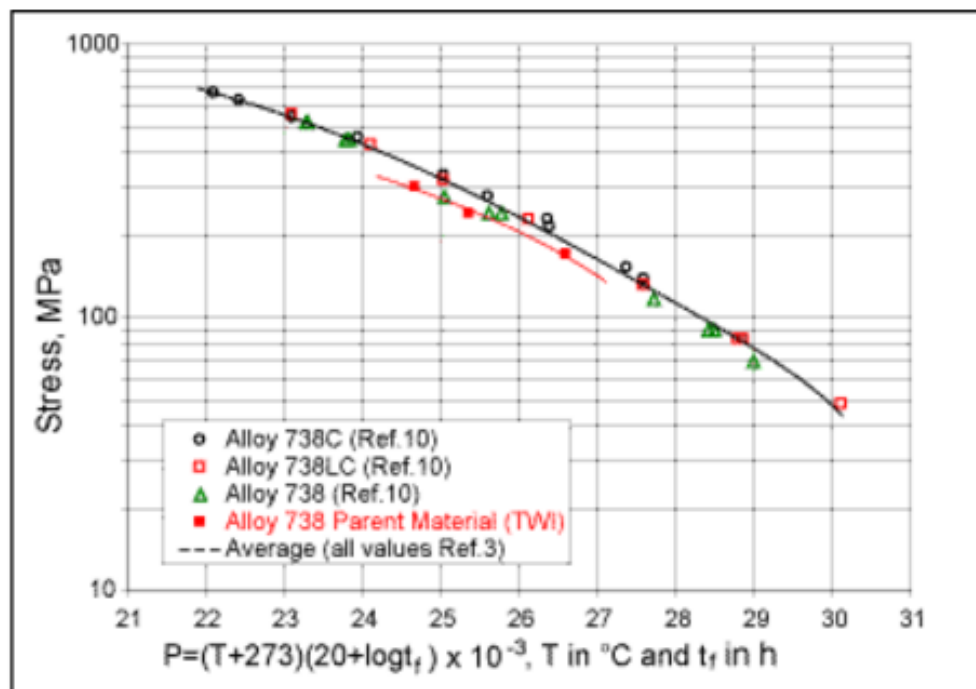
Creep-stress rupture data for high-temperature creep-resistant alloys are often plotted as log stress to rupture versus a combination of log time to rupture and temperature. One of the most common time-temperature parameters used to present this kind of data is the Larson-Miller (L.M.) parameter, which in generalized form is

$$P(L. M.) = T[\log t_r + C]$$

T = temperature, K

t_r = stress-rupture time, h

C = constant



Stress Relaxation Behavior

Relaxation is the counterpart of creep. It is the decline in stress with time, in response to a **constant applied strain, at constant temperature**. Stress relaxation behavior is one of the fundamental natures of polymers. At the time of stress relaxation, polymer molecules rotate due to the applied strain. The rearrangement of molecules continues as a function of time and reduces stress but maintains the strain level same. Figure below schematically illustrates the stress relaxation behavior of three different types of materials: elastic solid, viscous fluid, and viscoelastic material. Purely elastic material holds a constant stress level for an extended period of time; purely viscous material dissipates stress immediately and will come back to zero stress level, while viscoelastic material relaxes stress with time. Relaxation behavior of polymers is more often expressed by the stress relaxation modulus which changes as a function of time.

$$E_{rel.}(t) = \frac{\sigma(t)}{\epsilon_0}$$

Where $E_{rel.}(t)$ is the relaxation modulus, $\sigma(t)$ is the time-dependent stress, and ϵ_0 is the applied constant strain.

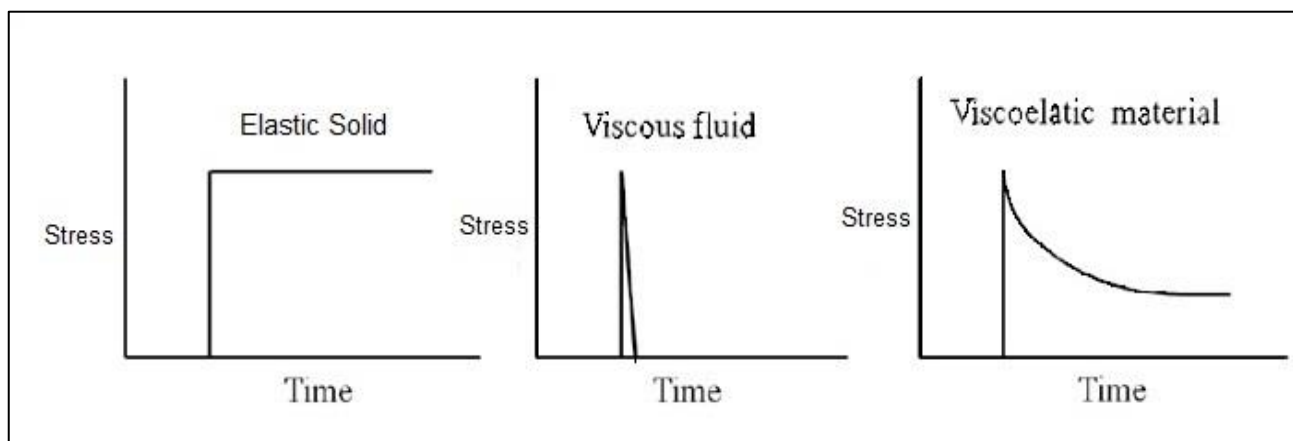


Figure ,Stress relaxation behavior of three different types of materials subjected to same amount of strain.

Viscoelastic Models

The stress strain time relation of viscoelastic material has been analyzed with the aid of mechanical models where the stress and strain instead of force and deformation of model are used. All linear viscoelasticity models are made up of linear spring and linear viscoelastic dashpot. The stress strain time relation of viscoelastic material has been analyzed with aid of mechanical models where the stress and strain instead of force and deformation of model are used.

In the linear spring shown in Figure. A spring models a perfectly elastic solid. The following relation can be written¹ :

$$\sigma = E \varepsilon$$

where: σ :stress , E : linear spring constant or Young's modulus, ε :strain

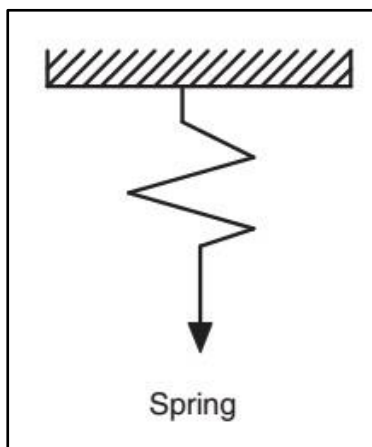


Figure linear spring

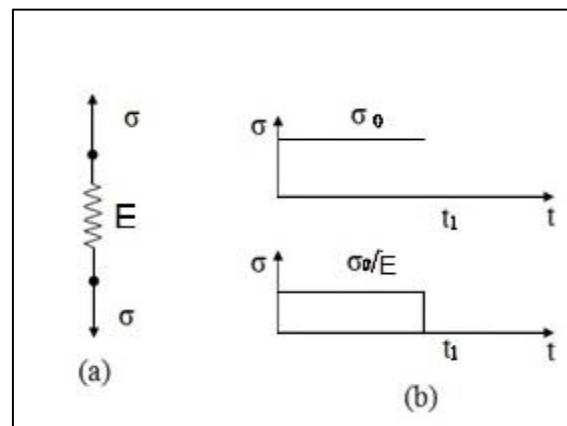


Figure behavior of linear spring

The spring element exhibits instantaneous elasticity and instantaneous recovery as shown in Figure. A linear dashpot element is shown in Figure . A dashpot model is a perfectly viscous material. where :

$$\sigma = \eta \frac{d\varepsilon}{dt} = \eta \dot{\varepsilon}$$

Where:

η = coefficient of viscoelasticity , $\dot{\epsilon}$ = strain rate.

Dashpot will be deformed continuously at constant rate when it is subjected to a step of constant stress as shown in Figure

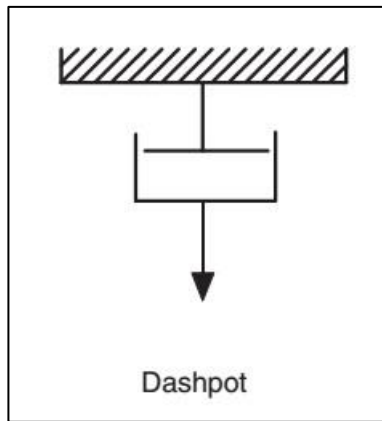


Figure Linear dashpot

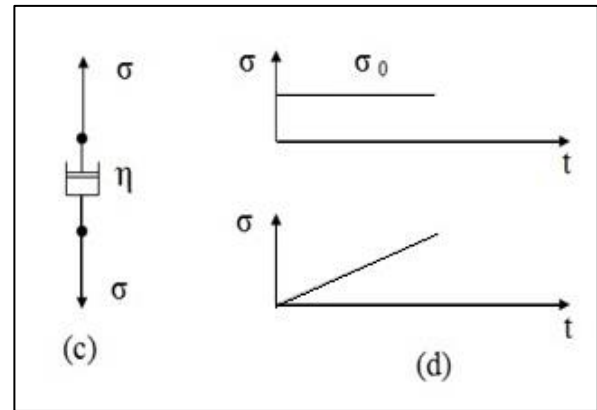


Figure Behavior of linear dashpot

Maxwell Model

The Maxwell model represents a viscoelastic material in which a mechanical model would be represented as a spring and a dash-pot in series. This model is intended to model a combination of elastic deformation and viscous flow. The Maxwell model is a two element model consisting of linear spring and linear dashpot element connected in series as shown in Figure . By examining the Maxwell model, it can be seen that the stress throughout the model is constant, while the strain would equal the sum of the two strain components, the Maxwell model may be expressed in terms of stress

The stress strain relation of spring and dashpot is derived from Eq.

as follows:

$$\sigma = E \epsilon_2 \quad \text{Or} \quad \epsilon_2 = \frac{\sigma}{E}$$

$$\sigma = \eta \dot{\epsilon} \quad \text{Or} \quad \dot{\epsilon}_1 = \frac{\sigma}{\eta}$$

Where: ϵ_2 = the strain in spring , $\dot{\epsilon}_1$ = the strain in dashpot.

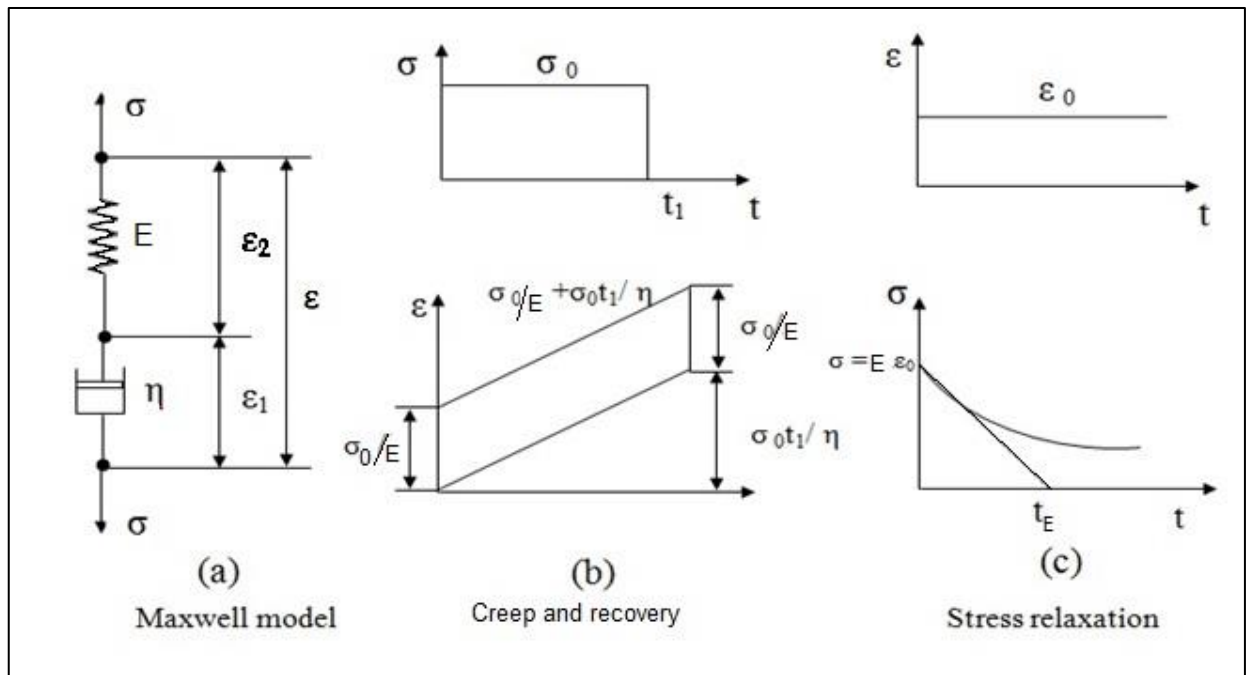


Figure Behavior of Maxwell model

Since both elements are connected in series, the total strain is:

$$\epsilon = \epsilon_2 + \epsilon_1$$

Or the rate of strain is:

$$\dot{\epsilon} = \dot{\epsilon}_2 + \dot{\epsilon}_1$$

$$\dot{\epsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\eta} \quad \dots \quad *$$

The equation of strain during time can be found by solving (*) for the following boundary initial condition: At $t=0$, $\sigma = \sigma_0$

After solving the first order differential equation (3.8), the strain time relation can be obtained as follows:

$$\epsilon(t) = \frac{\sigma_0}{E} + \frac{\sigma_0}{\eta} t$$

Also if the Maxwell is subjected to a constant strain (ϵ_0 at $t=0.0$) with initial stress value, the stress response can be obtained as :

$$\sigma(t) = \sigma_0 e^{-Et/\eta}$$

Kelvin Model

The Kelvin model (Voigt Model) used to model a damped elastic response is a parallel arrangement of the spring and dash-pot elements. In this arrangement, the strain in each individual component is equivalent to the total strain, and the total stress is the sum of the stresses in the individual components. By analyzing the creep modulus and relaxation modulus, further insight may be gained regarding the viscoelastic behavior of polymers.

In this model, spring and dashpot element are connected in parallel as shown in Figure. According to Eq. , the strain relation is :

$$\sigma_1 = E \varepsilon$$

$$\sigma_2 = \eta \dot{\varepsilon}$$

The total stress in the Kelvin model is:

$$\sigma = \sigma_1 + \sigma_2$$

$$\dot{\varepsilon} + \frac{E}{\eta} \varepsilon = \frac{\sigma}{\eta}$$

Equation can be solved as a first order differential equation for creep test for the following initial condition:

At $t=0.0$ and $\sigma = \sigma_0$. The solution being:

$$\varepsilon(t) = \frac{\sigma_0}{E} (1 - e^{-Et/\eta})$$

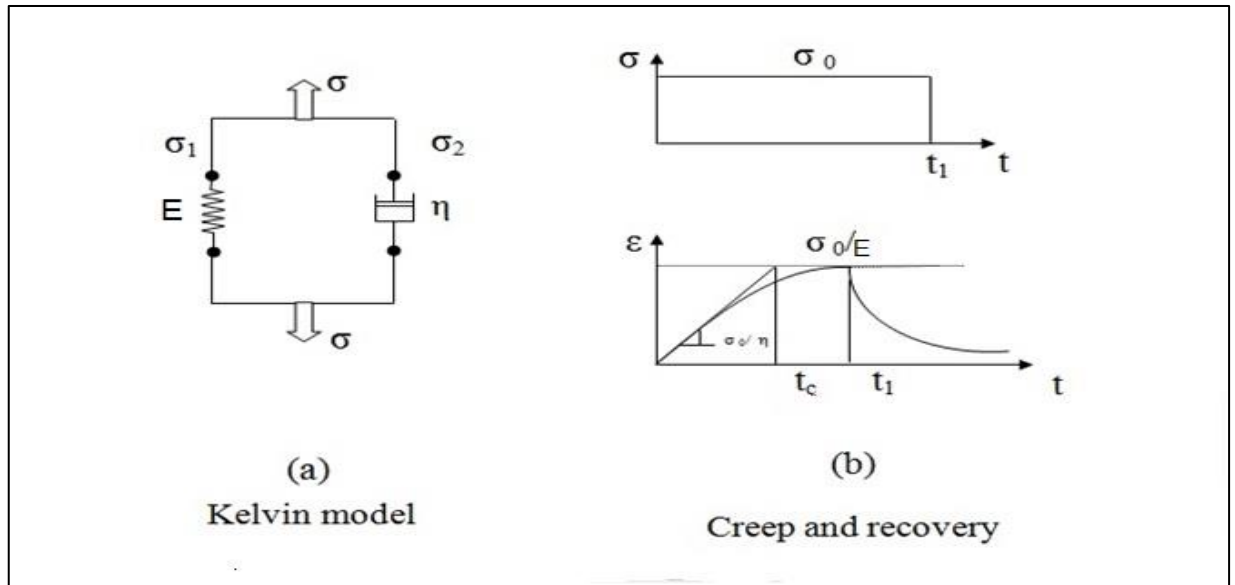


Figure Behavior of Kelvin model

Burger Four – Element Model

The burgers model is shown in Figure where the Maxwell and Kelvin model are connected in series.

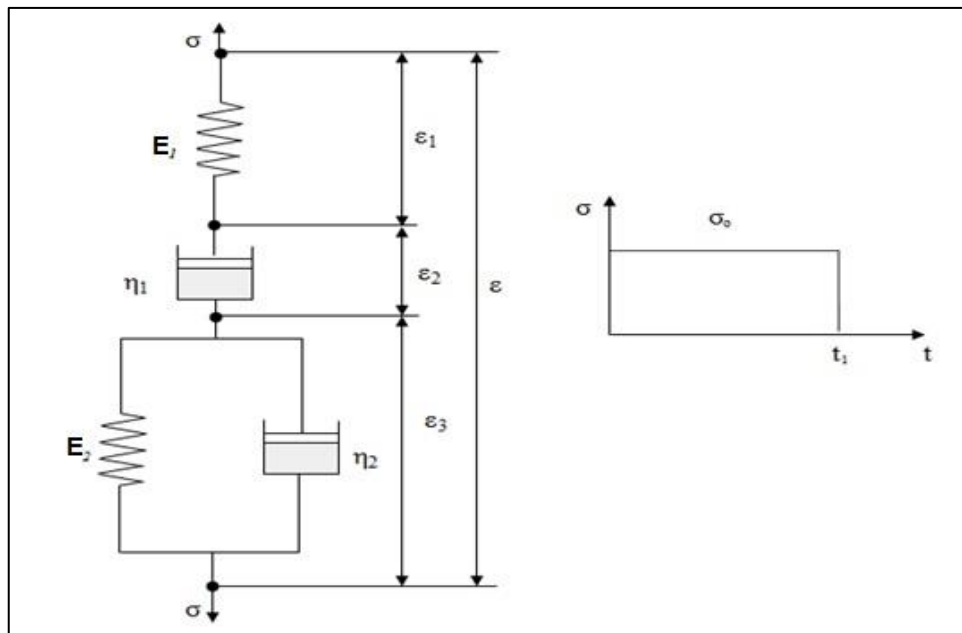


Figure Burger Model

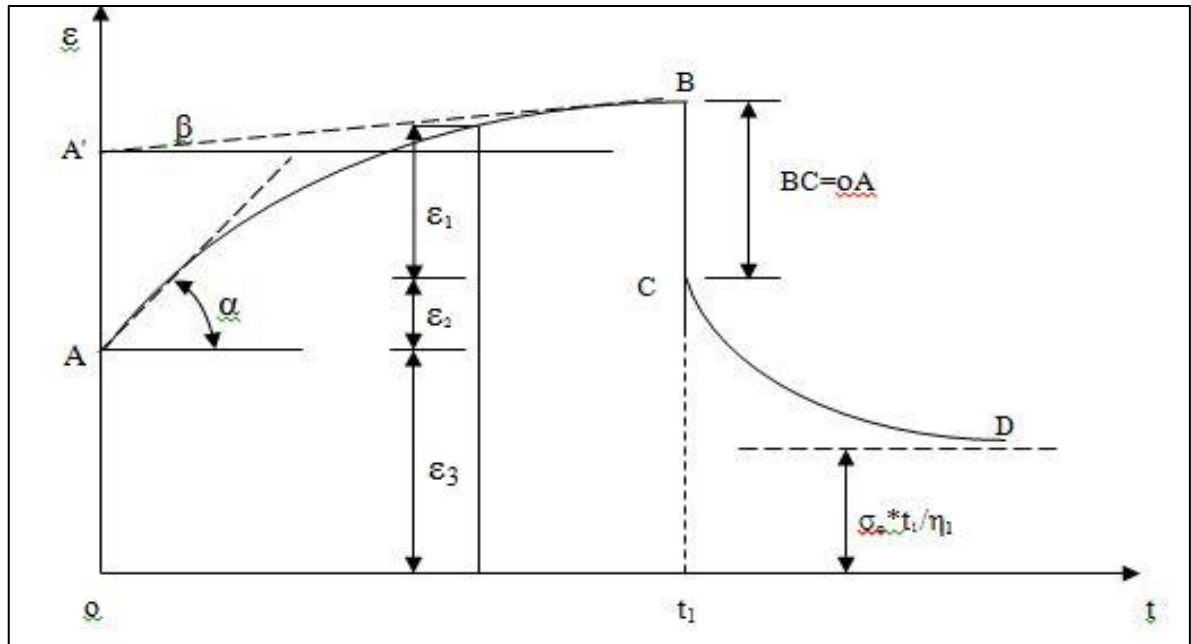


Figure Behavior of a Burger model (creep and recovery)

Standard Linear Solid

Most polymers do not exhibit the unrestricted flow permitted by the Maxwell model. Placing a spring in parallel with the Maxwell unit gives a very useful model known as the "Standard Linear Solid" (S.L.S.) shown in Figure . This spring has stiffness, so named because it provides an "equilibrium" or rubbery stiffness that remains after the stresses in the Maxwell arm have relaxed away as the dashpot extends.

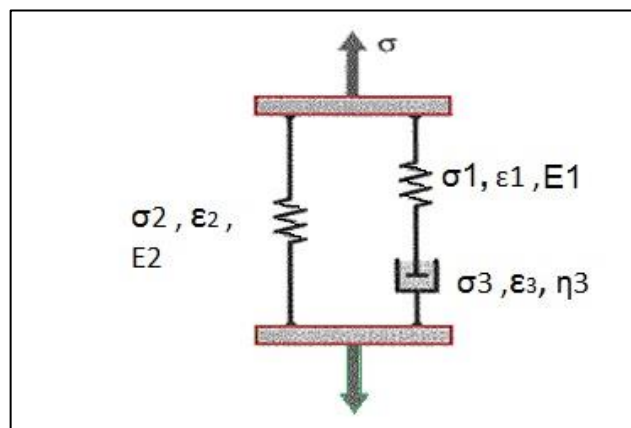


Figure the Maxwell form of the Standard Linear Solid .

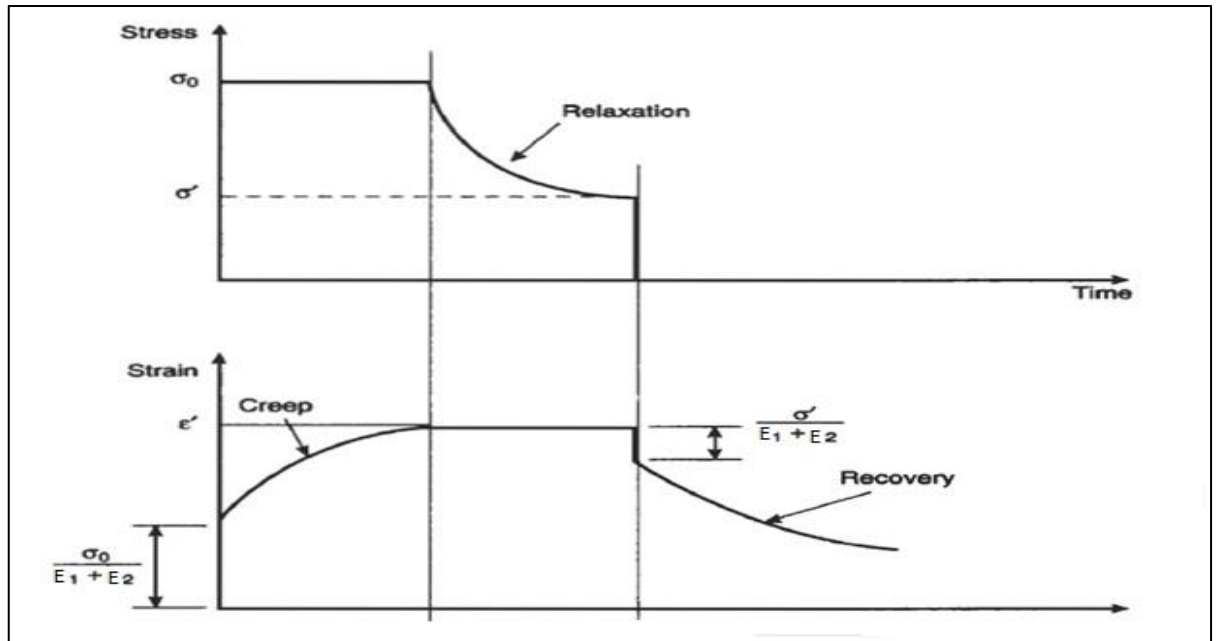


Figure. response of standard linear solid