
بسم الله الرحمن الرحیم

K. N. Toosi University of Technology
Faculty of Materials Science and Engineering

Selection of Engineering Materials

Seventh Session
(Material Selection Process- 5)

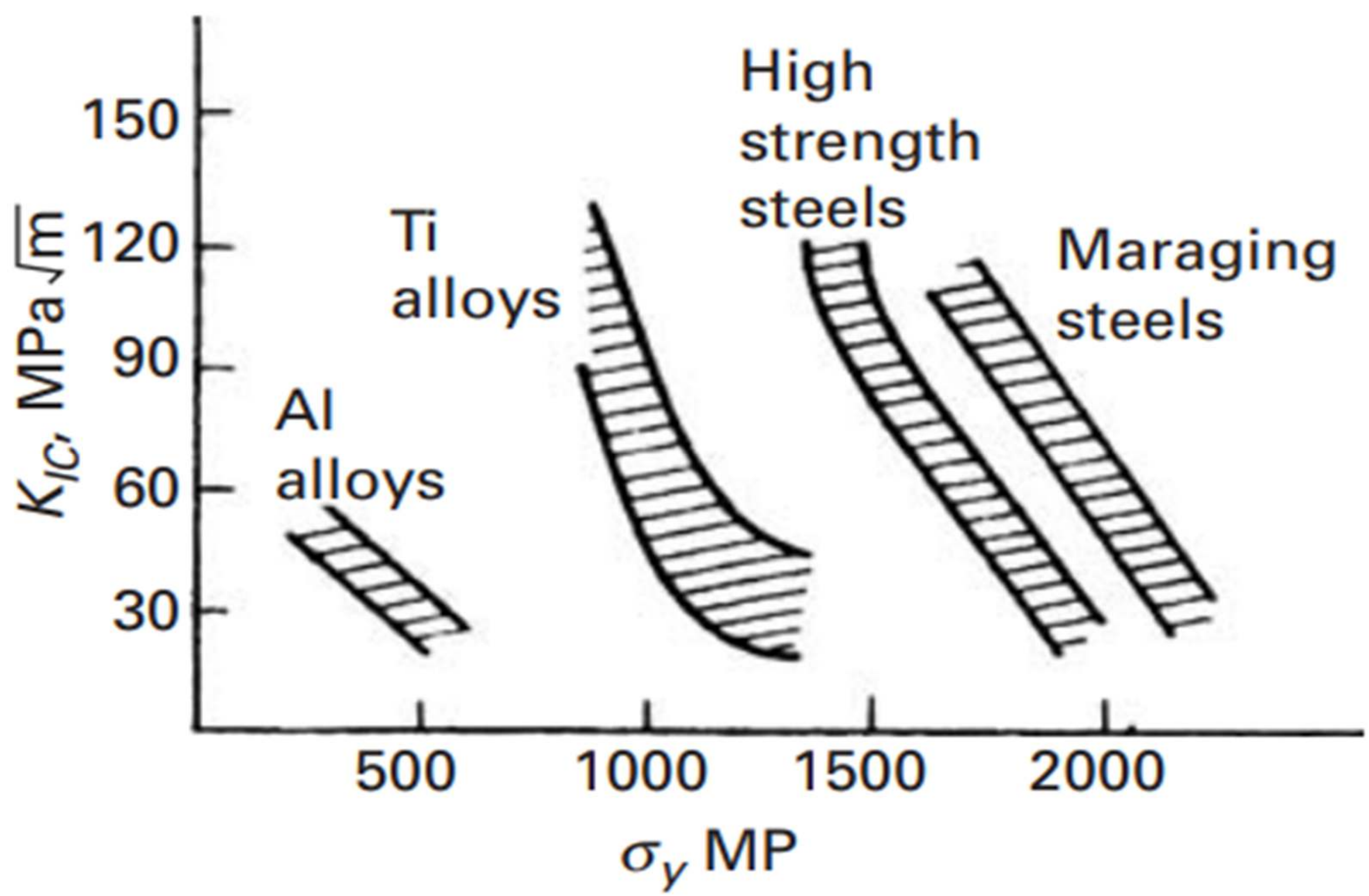
Reza Eslami-Farsani

Material Selection Based on Toughness Criterion

- ✓ Fracture toughness is related to other mechanical properties of materials. For many materials, fracture toughness decreases with increasing strength.
- ✓ Chemical composition and microstructure of materials are effective on fracture toughness. For example, in steels, the amount of brittle inclusions, the larger grain size and the increase in carbon percentage lead to a decrease in toughness.

Material Selection Based on Toughness Criterion

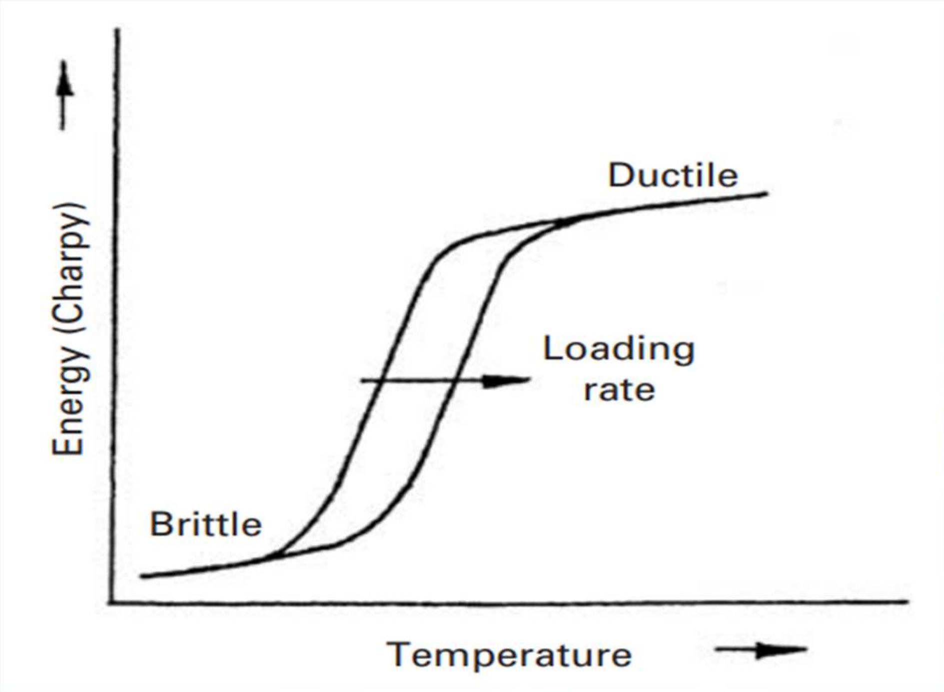
Diagram of Changes in Fracture Toughness According to Yield Strength



Material Selection Based on Toughness Criterion

- ✓ The presence of deoxygenating elements, such as aluminum also helps to refine the grain size and improve the fracture toughness.
- ✓ The ductile to brittle transition temperature (DBTT) of deoxygenated fine grain steels is low and these materials are more resistant to brittle fracture.

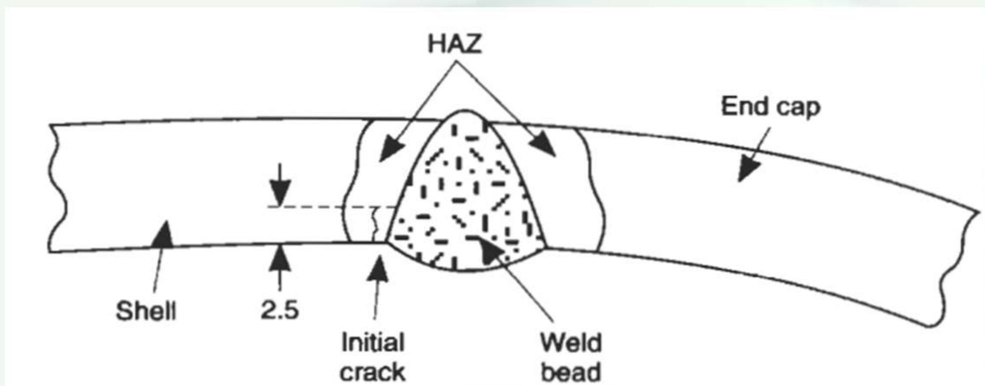
DBTT Diagram



Material Selection Based on Toughness Criterion

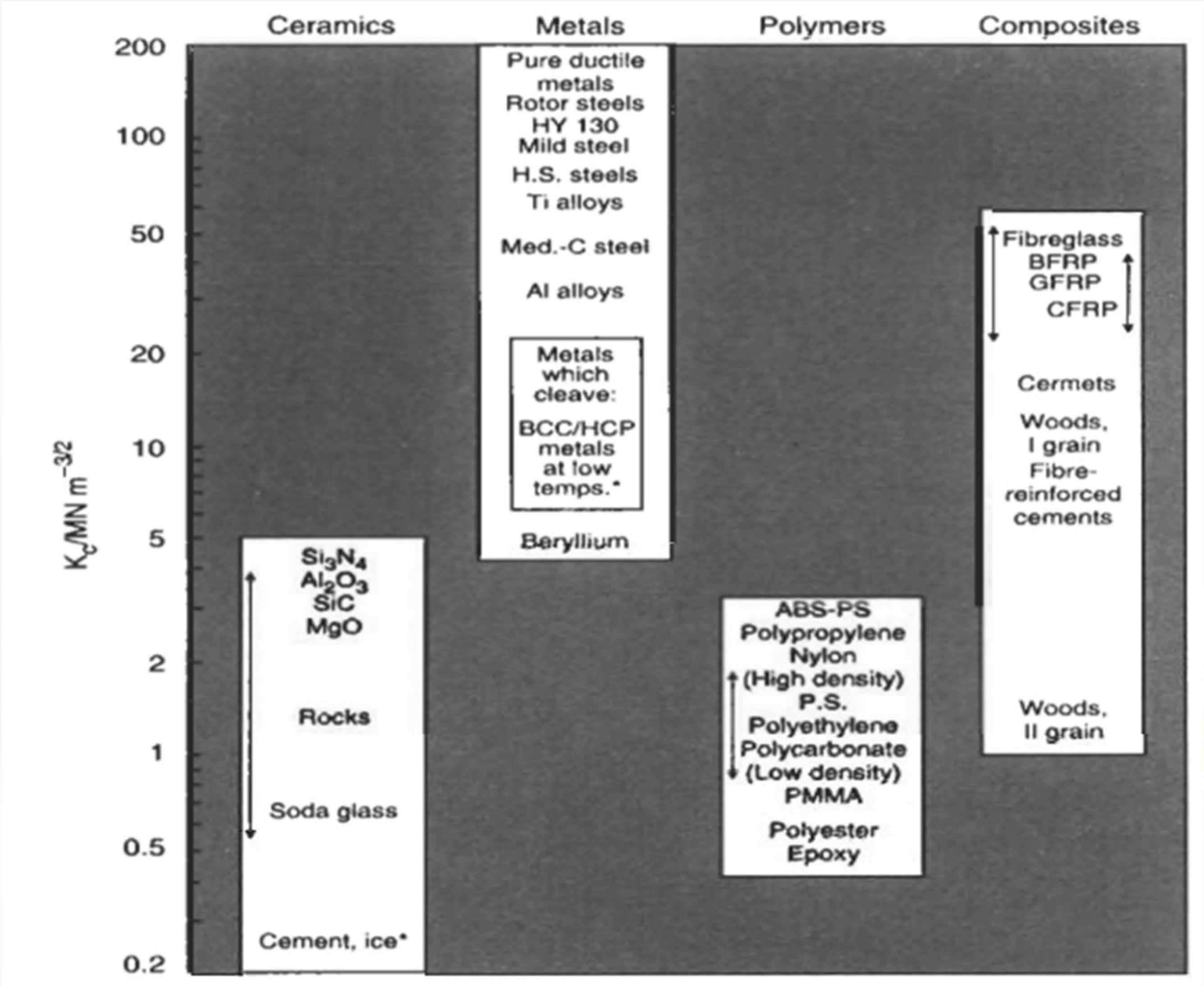
- The manufacturing process is very effective on toughness.
- The origin of many brittle fractures is the weld zone and its adjacent areas.
- Residual stresses created during welding and the presence of defects in the welding area are factors of these failures.
- Slow loading speed also causes tough behavior compared to brittle behavior for shock and instantaneous loading.

The initial crack, 2.5 mm deep, had formed in the heat-affected zone



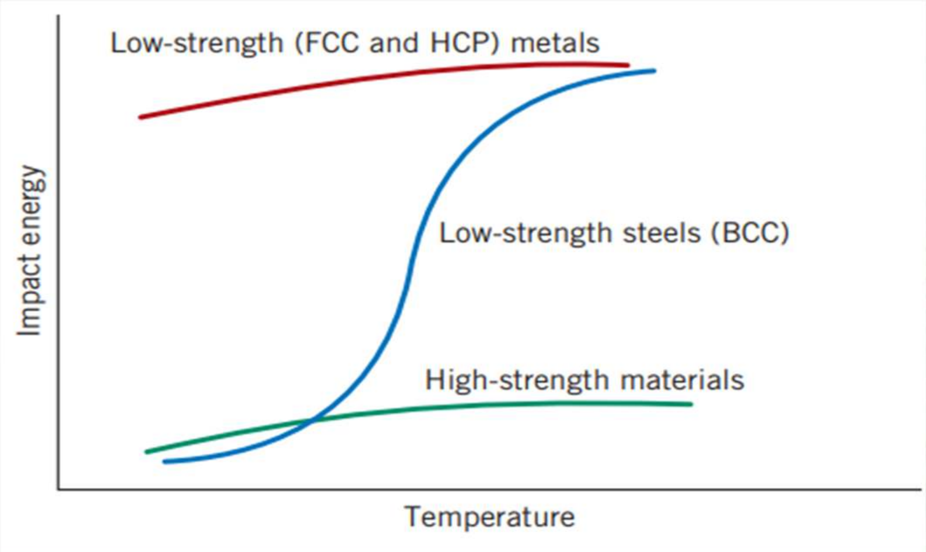
Material Selection Based on Toughness Criterion

Fracture Toughness, Kc (Values at Room Temperature Unless Starred)



Material Selection Based on Toughness Criterion

- ✓ Decreasing the temperature of the working environment is effective on the loss of toughness. This phenomenon is very important for metals with BCC lattice that have a brittle transformation temperature (such as some carbon steels). For example, in some cases, welded steel ships welded with BCC lattice have suffered brittle failure as the temperature of the working environment decreases.



Material Selection Based on Toughness Criterion

- Materials with BCC lattice are not suitable for low temperature and non-ferrous metals such as copper, aluminum and nickel alloys with FCC lattice and also austenitic steels should be used.

Titanic Ship

Material Selection Based on Toughness Criterion

- In the discussion of material selection based on toughness, the detection of cracks before reaching the critical value is one of the important aspects. Larger cracks are easily identified, so it is preferable to use materials that can withstand a larger critical crack.

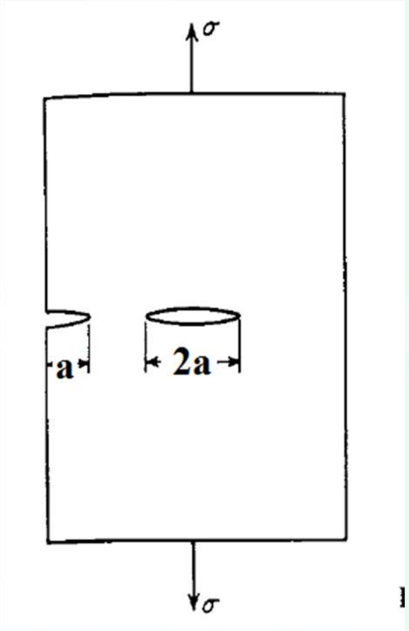
- The maximum allowable crack in a material is proportional to the ratio of the fracture toughness to the yield strength of that material at a given temperature and loading rate.

Material Selection Based on Toughness Criterion

- ✓ A higher value of the ratio of fracture toughness to yield strength indicates greater crack endurance capability. Therefore, in the selection of materials, it is necessary to combine the fracture toughness and yield strength with a critical crack detectable by non-destructive methods.
- ✓ The combination of fracture toughness, applied stress and crack length are effective on the fracture of a segment.

Material Selection Based on Toughness Criterion

Relationship Between Stress Level, Crack Size and Fracture Toughness



$$K_{IC} = \alpha \sigma_f \sqrt{\pi . a}$$

σ_f: Fracture stress

α: Correction coefficient, part geometry dependent (crack thickness, width and length)

a: Crack length (for internal cracks, the crack length is 2a and for edge cracks, the crack length is equal to a)

Different combinations of stress and crack length can cause structural failure with a specified fracture toughness (K_{IC}).

Material Selection Based on Toughness Criterion

- ✓ If a material with a certain K_{IC} is considered for a given application, it is possible to predict the crack size that will cause failure at the expected stress level.

- ✓ Having the design stress of the part and K_{IC}, the critical length of the crack is obtained (for example, a_1). Therefore, failure due to loading will not occur if there is no crack with a length greater than a_1. If in the stress test, the sample is loaded to a stress level higher than the expected stress during work and is not damaged, there are no cracks larger than a1 in it.

Material Selection Based on Toughness Criterion

- ✓ According to the relationship between stress, toughness and crack length, it can be concluded that if K_{IC} and yield stress are measured under the condition of loading rate and working temperature, the largest allowable crack is proportional to the ratio $(K_{IC}/Y_s)^2$.

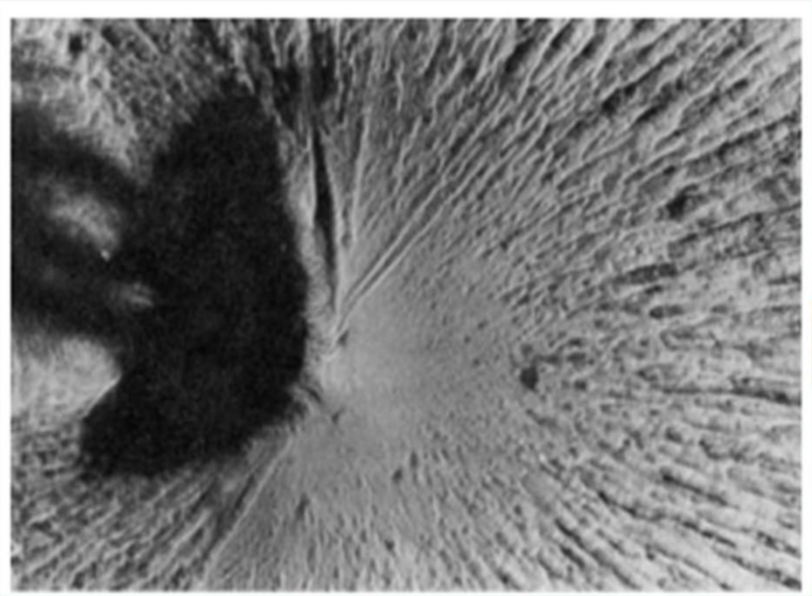
- ✓ This means that K_{IC}/Y_s is an index for comparing the toughness of structural materials and its higher values are more favorable. In this case, larger cracks are allowable.

Material Selection Based on Toughness Criterion

Polymers

- ✓ Similar to some metals, polymers have a brittle transformation temperature, which is called the glass transition temperature (Tg).
- ✓ At a temperature lower than Tg, the polymer is a brittle elastic solid, and at temperatures higher than Tg, it is the flexible elastic material.

Brittle fracture in a highly cross-linked thermoset (Polyester)



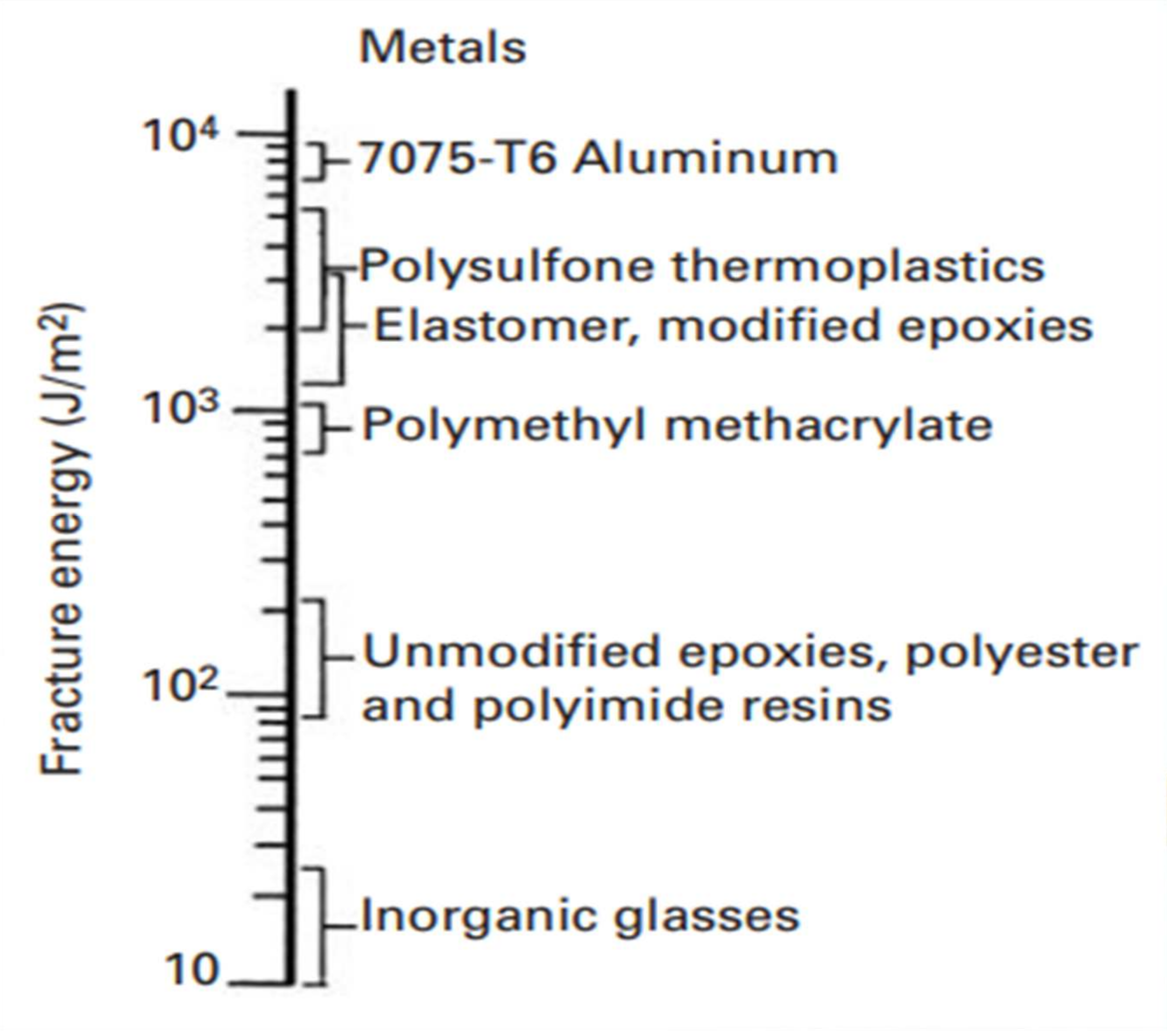
Material Selection Based on Toughness Criterion

To improve the toughness and impact strength of polymers, the following methods are applied:

- ✓ Alloying with another phase that has higher impact resistance (such as rubber phases), for example, nylon alloyed with polyolefin
- ✓ Copolymerization to create a tougher chemical structure
- ✓ Using reinforcements with greater impact resistance (such as fibers) in polymer fields, in other words, preparing composites

Material Selection Based on Toughness Criterion

Fracture Energy of Some Common Materials



Material Selection Based on Toughness Criterion

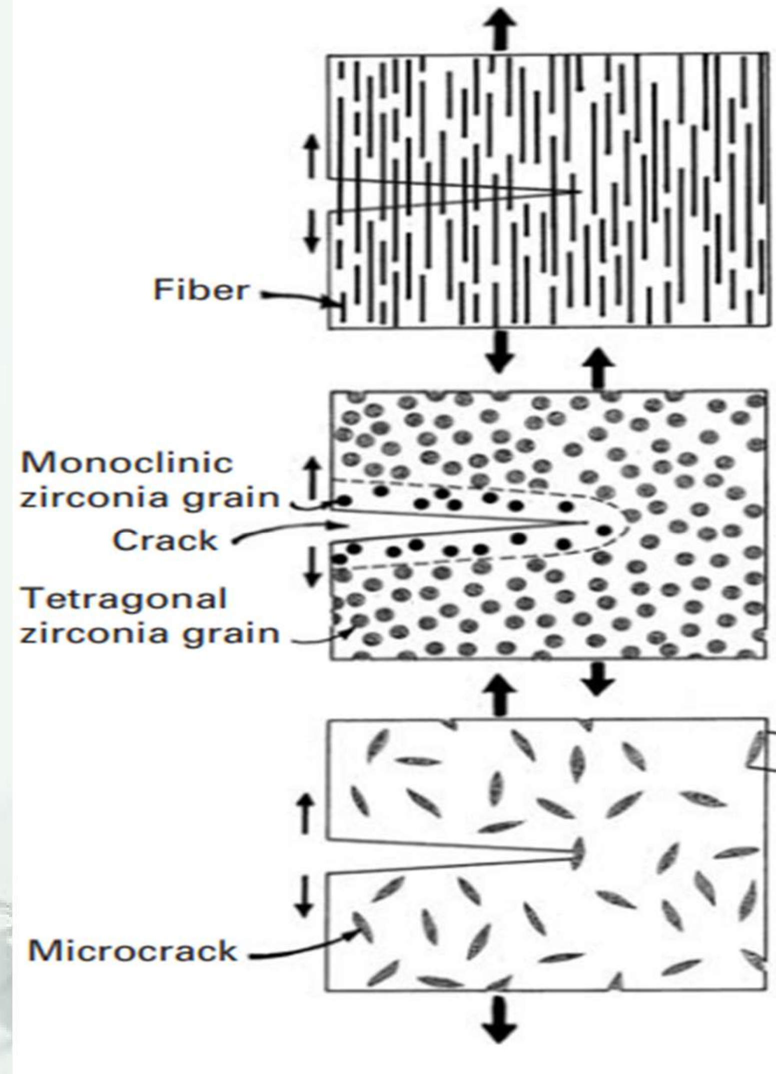
Ceramics

Ceramics are inherently brittle. To improve their toughness, the following methods are applied:

- ✓ Reinforcement with fibers and particles materials (composites)
- ✓ Creating a phase transformation in the stress applied region in the material. This transformation causes energy absorption at the tip of the expanding crack and stops the progress and increases the strength and toughness.

Material Selection Based on Toughness Criterion

- ✓ A third mechanism for toughening ceramics is to form microcracks ahead of the main crack. The microcracks have the effect of decreasing the stress intensity factor at the root of the principal crack. An additional effect is that they can lead to crack branching.



Selection of Materials for Heat Resistance

- ✓ Creep is the limiting factor in the service life of parts or structures at high temperatures.

- ✓ Many methods of strengthening metals at low temperatures lose their effectiveness at temperatures above half of the melting point (in Kelvin).

Selection of Materials for Heat Resistance

- ✓ At high temperatures, the mobility of atoms causes the softening of cold structures and coarsening of unstable precipitates.

- ✓ The best way to improve the creep strength is to introduce stable second phase particles in the form of very fine and dispersed distribution inside the grains.

Selection of Materials for Heat Resistance

- ✓ By complicating the chemical composition of precipitates and reducing the energy of the interface between the precipitate and the matrix in order to reduce the driving force of particle growth, more stable precipitates with less tendency to grow can be achieved.
- ✓ Deposition in the grain boundaries slows down the sliding in the grain boundaries and by controlling the ductility, it prevents the creep rupture and premature fracture of the material.

Selection of Materials for Heat Resistance

Suitable materials for each temperature are determined according to the permissible temperature range of application.

Ambient Temperature up to 150 °C

150-400 °C

400-600 °C

600-1000 °C

Above 1000 °C

Materials Performance at High Temperature

Ambient Temperature up to 150 °C

- ✓ All metals and engineering alloys except lead can be used in this temperature range. Some thermoplastics can also be used for long periods of time at temperatures above 100°C.
- ✓ Polycarbonates, polyether ether ketone and polypropylene can be used up to 200 °C.
- ✓ Some plastics reinforced with fibers such as nylon-glass fibers are also used in this temperature range.

Materials Performance at High Temperature

Temperature 150 to 400 °C

- ✓ Plain carbon steels or manganese carbon steels are suitable for this range, but for long periods (more than 20 years) low alloy steels should be used.
- ✓ Engine casting parts for operation up to 250 °C can be made from alloy cast iron.
- ✓ Aluminum alloys can also be used up to 250 °C.

Materials Performance at High Temperature

Temperature 150 to 400 °C

- ✓ High temperature plastics are used up to 200 °C and for short periods up to 300 °C. Polysulfones, polyphenylene sulfides and polyether sulfones are among these plastics. Plastics composites such as thermosetting polyimides/carbon fibers are used in the range of 260-290 °C.
- ✓ Some new plastics such as polyparaphenylene benzobisoxazole are designed for long-time work up to 370 °C.

Temperature 400 to 600 °C

- ✓ In this temperature range, low alloy steels and titanium alloys are the best choices. If we do not have a weight limitation, low alloy steels (containing Cr, Mo and V) are used due to their cheapness.
- ✓ To improve creep resistance, steel with 5-12% chromium and some molybdenum is recommended.
- ✓ Titanium alloys with α phase structure have better creep resistance than β phase structure. Alloys close to alpha can be used up to 600 °C.

Temperature 600 to 1000 °C

- ✓ Four classes of alloys are used for this temperature range: stainless steels, Fe-Ni-based, Ni-based and Co-based superalloys.
- ✓ As the working temperature increases, the importance of corrosion and oxidation resistance in alloys increases. Oxidation resistance is a function of the amount of Cr, and especially at higher temperatures, Al improves it. Cr also causes resistance to hot corrosion, and the highest resistance is achieved with more than 20% Cr.

Materials Performance at High Temperature

Temperature 600 to 1000 °C

- ✓ In cases where the resistance to oxidation and hot corrosion of the alloy is insufficient, thermal barrier coatings are used. Diffusion coatings (CoAl and NiAl) and non-diffusion coatings (FeCrAl, CoNiAl and CoNiAly), which are added as a separate layer on the surface, are used in these cases.

A Coated High Pressure Compressor Blade Belongs to the Turbofan Engine

Materials Performance at High Temperature

Temperature 600 to 1000 °C

Stainless Steels

- ✓ Ferritic stainless steels (type 400) are used for applications with low stress and temperatures up to 650 °C.
- ✓ Austenitic stainless steels are used up to 750 °C, and the types 200 and 300 are more expensive than ferritic.
- ✓ High alloys 19-9DL and 19-9DX grades, containing Mo and Ti have higher strength and can work up to a temperature of 815 °C.

Temperature 600 to 1000 °C

Iron-Nickel Base Superalloys

They mainly contain a solid solution with an FCC lattice, which is strengthened by precipitates of intermetallic compounds and carbides. The usual precipitate in these alloys is Ni3(AlTi). Other precipitates are carbide nitride type.

Temperature 600 to 1000 °C

Nickel Base and Cobalt Base Superalloys

In nickel-based superalloys, the matrix with FCC lattice is strengthened by precipitates of intermetallic compounds. In this case also, Ni3(AlTi) precipitates, oxide particles or carbide precipitates cause strength. In cobalt-based superalloys, solid solution and carbide precipitates as strengthening agents have been used.

Temperatures above 1000 °C

Molybdenum, Niobium, Tantalum and Tungsten

- ✓ Only refractory metals such as molybdenum, niobium, tantalum and tungsten can be used in parts under load above 1000 °C.
- ✓ Niobium is used to contact molten Li and K-Na alloys at temperatures even higher than 800 °C. Addition of 1% zirconium to niobium increases the resistance to brittleness caused by oxygen absorption.

Materials Performance at High Temperature

Temperatures above 1000 °C

Molybdenum, Niobium, Tantalum and Tungsten

- ✓ Tantalum is used for constructional purposes in the temperature range of 1370-1980 °C, but due to its low resistance to oxidation, surface protection is essential. This metal is used as a thermal shield and thermal elements in vacuum furnaces.

Temperatures above 1000 °C

Molybdenum, Niobium, Tantalum and Tungsten

- ✓ Tungsten due to its higher melting point rather than niobium and tantalum, is the only choice for very high temperature constructional applications. In the filament of tungsten lamp, molybdenum is used to improve machinability and rhenium to resist brittle fracture.

Temperatures above 1000 °C

Molybdenum, Niobium, Tantalum and Tungsten

- ✓ The surface protection of refractory metals used in high temperature and oxidizing environment is the biggest obstacle to their widespread use. There are various types of aluminide and silicide coatings, which permissible working temperature is less than 1650 °C.

Plastics

- ✓ The strength of plastics at high temperature is generally evaluated by their deflection temperature under a certain load, known as DTUL (deflection temperature under load). This criterion is the temperature at which a deflection of 0.25 mm occurs in the sample under a load of 455 or 1820 kPa. The heating rate is a constant value of 2 °C/min.

Plastics

- ✓ Generally, thermosetting plastics are more resistant to heat than thermoplastic ones. Of course, using carbon or glass or mineral or ceramic fibers in the thermoplastics can effectively improve DTUL.

- ✓ The presence of 30% glass fibers in nylon increases the DTUL variable from 71 to 249 °C. Most plastics, if exposed to a temperature of 500 °C for a long time, will have a severe drop in mechanical properties and thermal collapse.