بسمه تعالی

دانشگاه شهید بهشتی

پردیس فنی و مهندسی شهید عباسپور

دانشکده مهندسی مکانیک و انرژی

درس دوره کارشناسی رشته مهندسی مواد و متالورژی

طراحی و انتخاب مواد مهندسی

(Engineering Design and Materials Selection)

بخش دوم – انتخاب مواد با معیارهای کاربردی

مدرس:

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عناوین و سرفصل ها

معیار های مختلف انتخاب مواد:

- استحکام ایستا
- چقرمگی
- سفتی
- خستگی
- خزش
- خوردگی
- ...

Used and Some Useful References:

- Selection and Use of Engineering Materials; *(J.A. Charles, F.A.A. Crane & J.A.G. Furness;* Butterworth-Heinemann *)*
- ASM Metals Handbook, Vol. 1,2: Properties and Selection, (ferrous & nonferrous alloys)
- Key to Steel, (*C.W. Wegst*; Verlag Stahlschlussel Wegst GMBH)
- Engineering Materials 1: An Introduction to Properties, Applications, and Design*; (M. F. Ashby & D. R. H. Jones)*
- Elsevier Materials Selector, Vol. 1,2,3; *(N.A. Waterman & M.F. Ashby;* Elsevier Science*)*
- Handbook of Materials Selection; *(Myer Kutz;* John Wiley & Sons*)*
- ASM Metals Handbook, Vol. 20: Materials Selection and Design; *(*ASM International*)*
- Structure and Properties of Engineering Alloys ; *(W.F. Smith;* McGraw-Hill*)*
- شناسایی، انتخاب و کاربرد مواد، (ح. *عالی، ح. غیاثوند،* س.ر. *علمی حسینی،* م.ر. رهگذر؛ جهان جام جم)
- تئوری و عملی متالورژی، *(د. ک. آلن، ترجمه ع.ا. قاری نیت)*
- *and other related references.*

انتخاب مواد برای کاربردهای

استحکام ایستا

Static Strength

Static strength

The term 'strength' is often used rather loosely. There are three distinct usages:

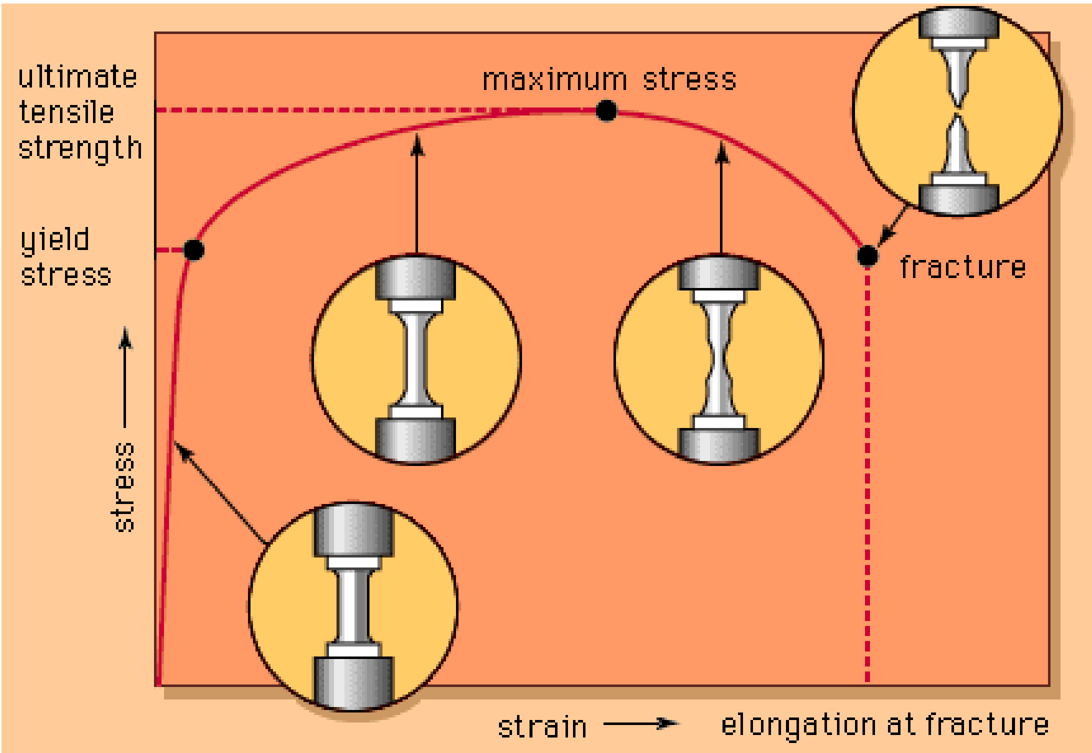
(1) *static strength* – the ability to resist a short-term steady load at normal room temperature;
(2) *fatigue strength* – the ability to resist a fluctuating or otherwise time-variable load;
(3) *creep strength* – the ability to resist a load at temperatures high enough for the load to produce a progressive change in dimensions over an extended period of time.

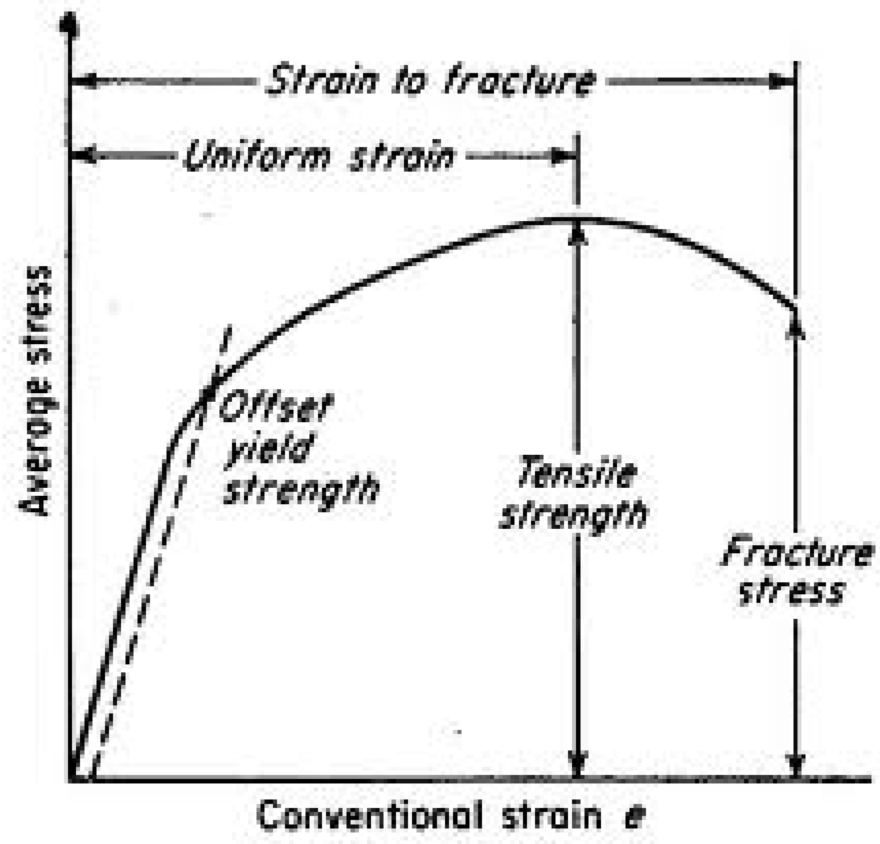
A proper understanding of the strength of a material generally requires the determination of its stress-strain curve either in tension, compression or shear: from this several parameters of strength can be taken, according to the relevant mode of failure.

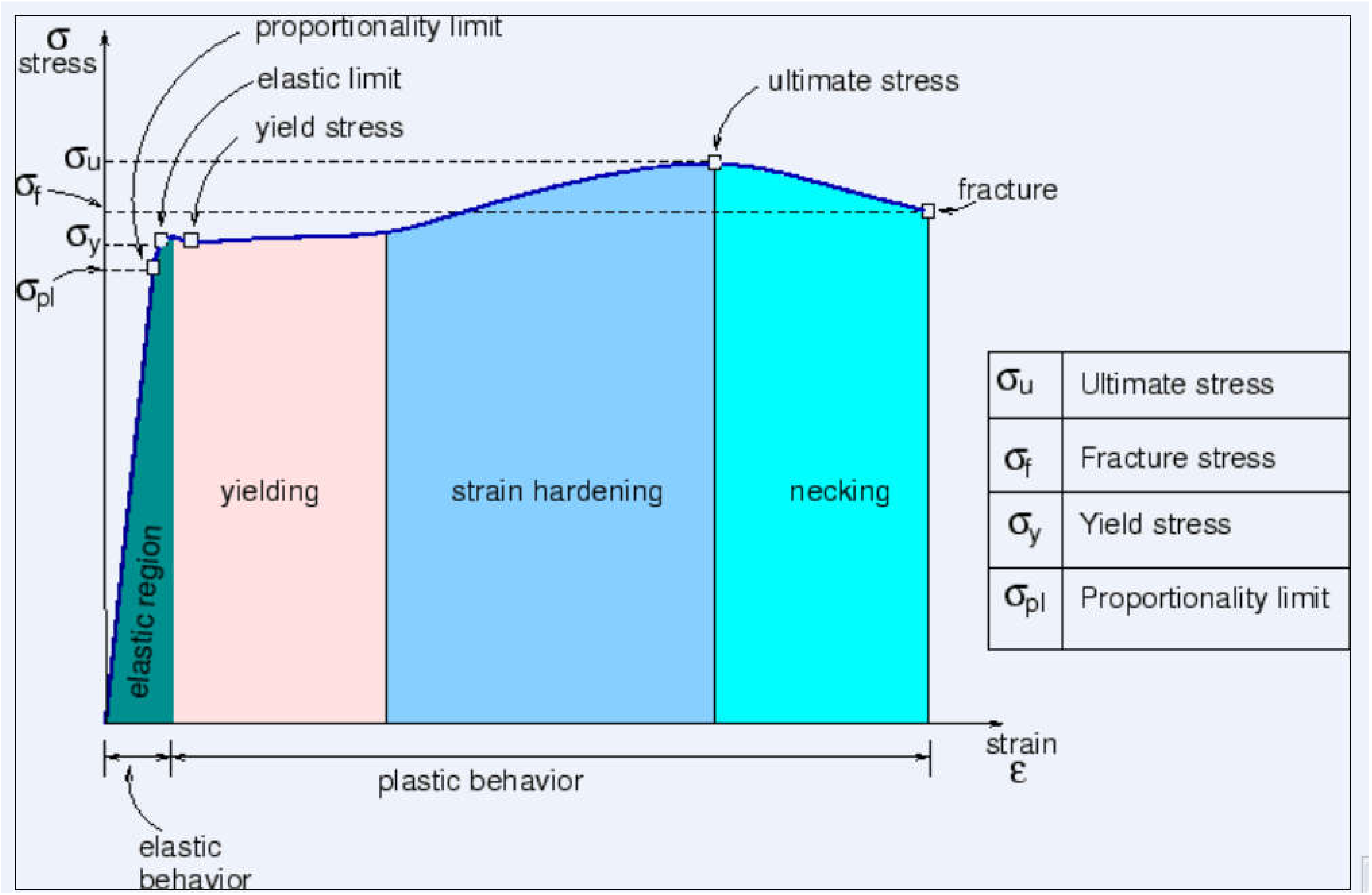
Because of the relative ease with which the tensile test can be carried out, most strength data for metals are obtained in tension; relative to these, compression data are sparse. However, concrete and ceramics are commonly tested in compression. Plastics, on the other hand are frequently tested in flexure.

- استحکام ایستا (Static Strength) اطلاعاتی است که از منحنی **تنش-کرنش مهندسی** **(S-e)** حاصل از تست کشش تک محوری (tensile test) در دمای محیط و شرایط آزمایشگاهی بدست می آید. Room Temp. , $d\varepsilon/dt \approx 10^{-3}$ /s

- تحمل بار در کوتاه مدت (غیر خزشی) و در دمای معمول






σ
stress
proportionality limit
elastic limit
yield stress
ultimate stress
σu
σf
σy
σpl
fracture
elastic region
yielding
strain hardening
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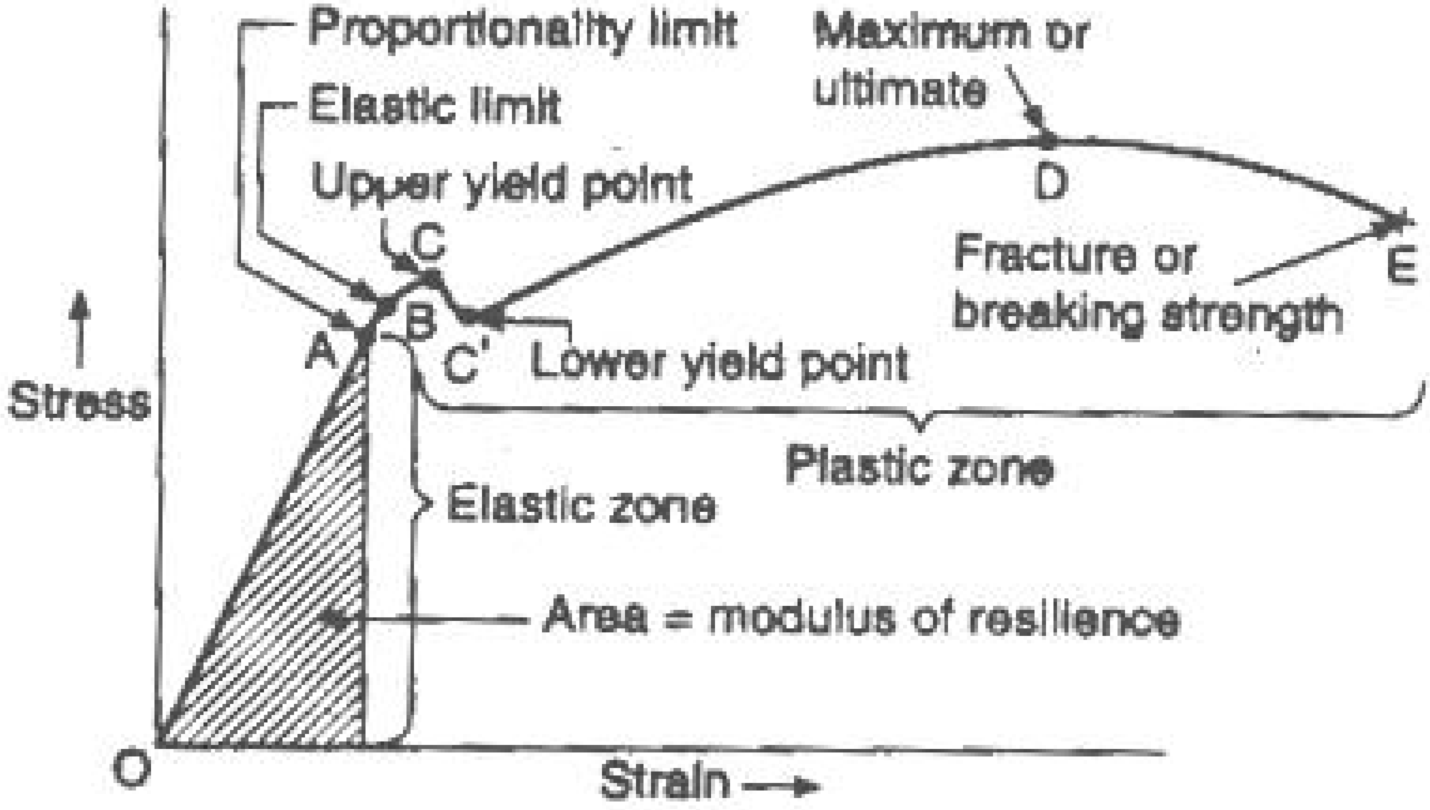
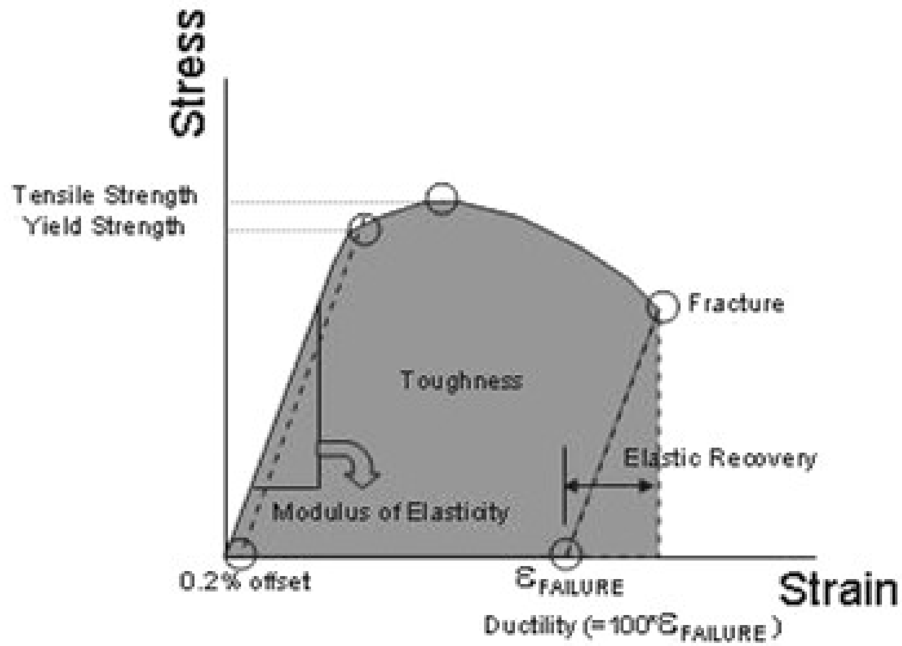
strain
ε
plastic behavior
elastic
behavior
σu Ultimate stress
σf Fracture stress
σy Yield stress
σpl Proportionality limit





$$\text{Modulus of resilience} = \frac{1}{2}\sigma_y \varepsilon = \frac{1}{2}\frac{\sigma_y^2}{E}$$

1.1 DEFINITION OF STRESS AND STRAIN

Before discussing engineering material stress–strain response, it is appropriate to define the terms, stress and strain. This may be done in two generally accepted forms. The first definitions, used extensively in engineering practice, are

$$\sigma_{eng} = \text{engineering stress} = \frac{\text{load}}{\text{initial cross-sectional area}} = \frac{P}{A_0} \qquad (1\text{-}1a)$$

$$\epsilon_{eng} = \text{engineering strain} = \frac{\text{change in length}}{\text{initial length}} = \frac{l_f - l_0}{l_0} \qquad (1\text{-}1b)$$

where l_f = final gage length
l_0 = initial gage length

Alternatively, stress and strain may be defined by

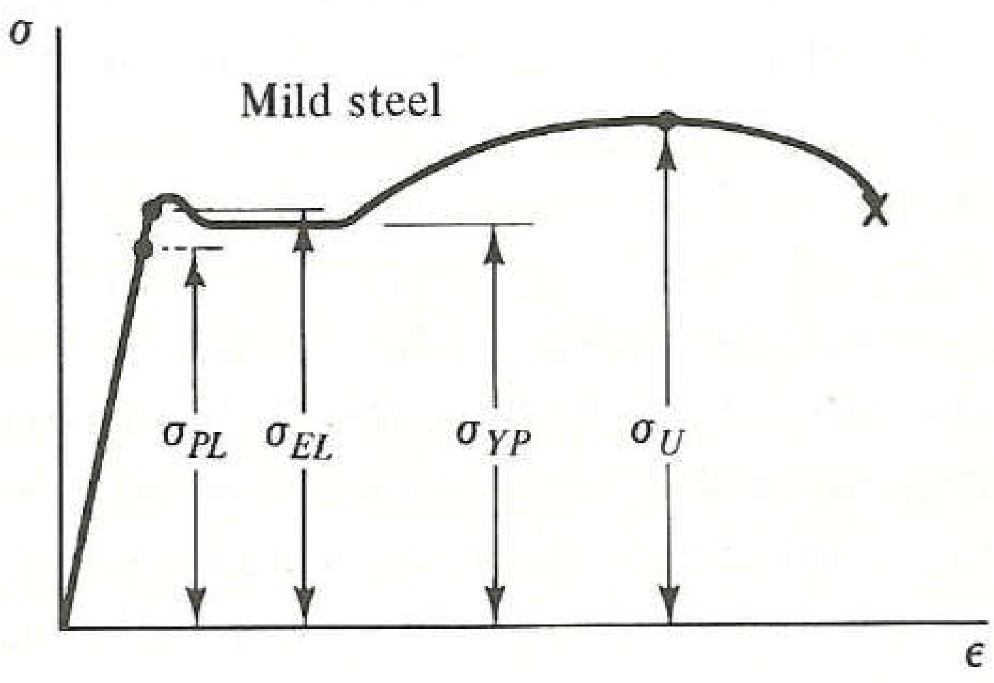
$$\sigma_{true} = \text{true stress} = \frac{\text{load}}{\text{instantaneous cross-sectional area}} = \frac{P}{A_i} \qquad (1\text{-}2a)$$

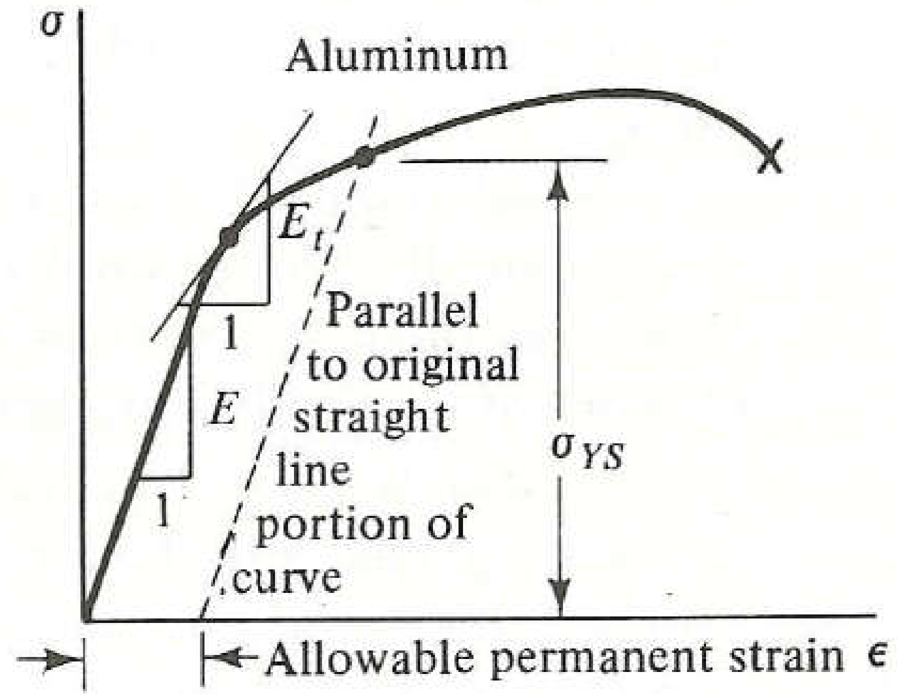
$$\epsilon_{true} = \text{true strain} = \ln \frac{\text{final length}}{\text{initial length}} = \ln \frac{l_f}{l_0} \qquad (1\text{-}2b)$$

$$\sigma_{true} = \sigma_{eng}(1 + \epsilon_{eng})$$

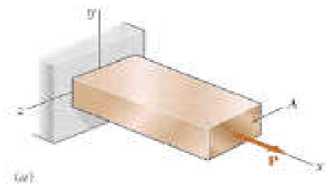
$$\epsilon_{true} = \ln(\epsilon_{eng} + 1)$$

(R.W. Hertzberg)





$$\sigma = E\epsilon$$



$E = \sigma/\varepsilon$ (normal stress – strain)

$G = \tau/\gamma$ (shear stress – strain)

E = Elastic Modulus or Modulus of Elasticity
G = Shear Modulus or Modulus of Rigidity

$G = E / 2(1+\nu)$

$$\nu = -\frac{\varepsilon_y}{\varepsilon_x} = -\frac{\varepsilon_z}{\varepsilon_x}$$

Poisson's ratio for most materials ranges from 0.25 to 0.35.

$$\varepsilon_y = \varepsilon_z = -\frac{\nu\sigma_x}{E}$$

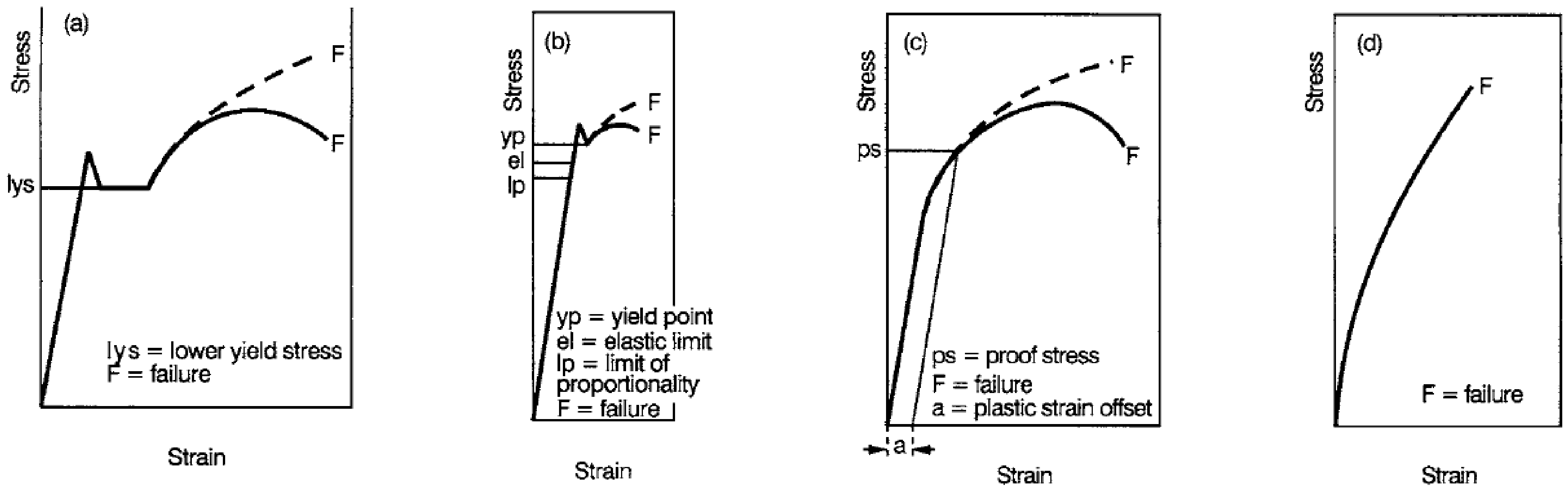
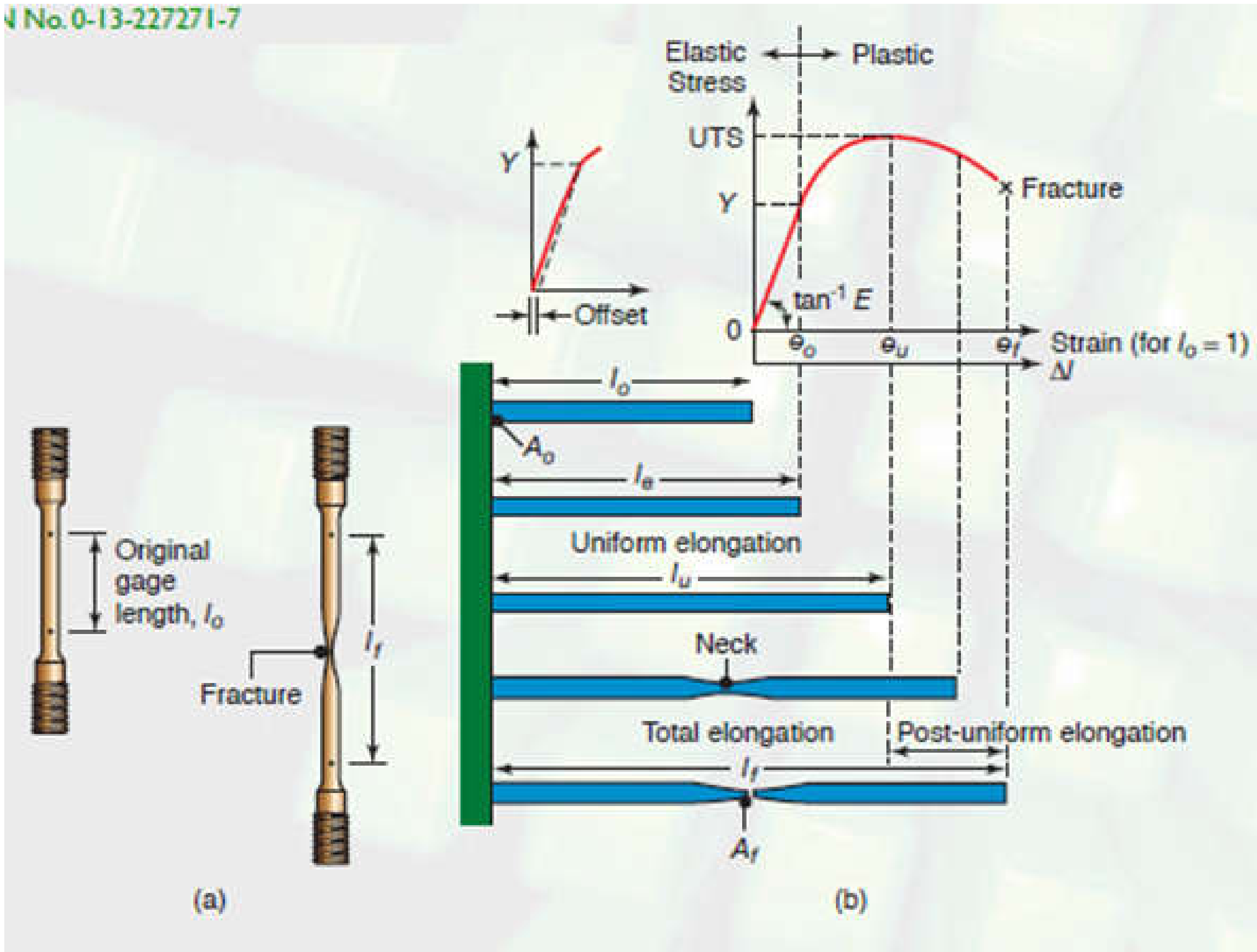


Figure 6.2 Stress–strain curves for metals: (a) impure iron, (b) medium-carbon steel, (c) hard brass, and (d) grey cast iron. Dotted line indicates true stress, taking into account the ductile reduction of cross section.

Figure 6.2c is typical of materials which undergo continuous yielding. The smooth transition from the fully elastic to the elastic-plastic regime means that there is no clear singularity available to provide a definition of general yielding. The usual procedure is to measure the stress for a certain plastic strain and call this the proof stress. Values may be reported for plastic strains of 0.5, 0.2, 0.05 or even 0.01%, but for general engineering purposes 0.1 or 0.2% proof stresses are preferred. **(0.2% offset)**

- در تست کشش، مقدار کرنش نهایی شکست وابسته به ابعاد نمونه است
- کرنش مربوط به نقطه ماکزیمم تنش (e_{uts})، مدول یانگ و UTS مستقل از ابعاد
- در تست کشش استاندارد باید L_0/D_0 یا $L_0/\sqrt{A_0}$ مشخص باشد.



$$e_f = e_{uts} + \beta \frac{\sqrt{A_0}}{L_0}$$

True Stress-True Strain for Various Materials

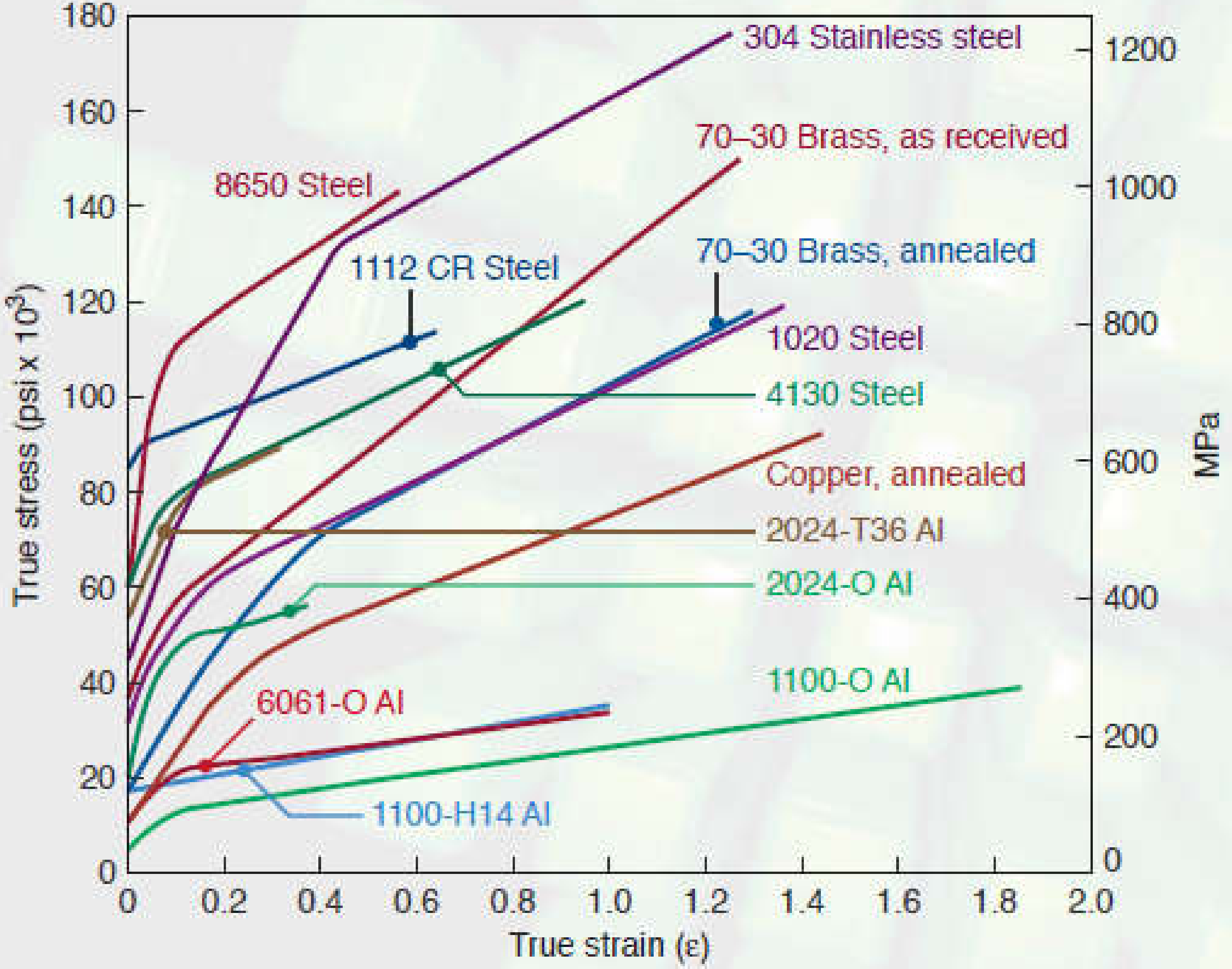


FIGURE 2.6 True stress-true strain curves in tension at room temperature for various metals. The point of intersection of each curve at the ordinate is the yield stress *Y*; thus, the elastic portions of the curves are not indicated. When the *K* and *n* values are determined from these curves, they may not agree with those given in Table 2.3 because of the different sources from which they were collected. *Source:* S. Kalpakjian.

Manufacturing Processes for Engineering Materials, 5th ed.
Kalpakjian • Schmid

ISBN No. 0-13-227271-7

	E (GPa)	Y (MPa)	UTS (MPa)	Elongation in 50 mm (%)	Poisson's Ratio (ν)
METALS (WROUGHT)					
Aluminum and its alloys	69-79	35-550	90-600	45-5	0.31-0.34
Copper and its alloys	105-150	76-1100	140-1310	65-3	0.33-0.35
Lead and its alloys	14	14	20-55	50-9	0.43
Magnesium and its alloys	41-45	130-305	240-380	21-5	0.29-0.35
Molybdenum and its alloys	330-360	80-2070	90-2340	40-30	0.32
Nickel and its alloys	180-214	105-1200	345-1450	60-5	0.31
Steels	190-200	205-1725	415-1750	65-2	0.28-0.33
Stainless steels	190-200	240-480	480-760	60-20	0.28-0.30
Titanium and its alloys	80-130	344-1380	415-1450	25-7	0.31-0.34
Tungsten and its alloys	350-400	550-690	620-760	0	0.27
NONMETALLIC MATERIALS					
Ceramics	70-1000	—	140-2600	0	0.2
Diamond	820-1050	—	—	—	—
Glass and porcelain	70-80	—	140	0	0.24
Rubbers	0.01-0.1	—	—	—	0.5
Thermoplastics	1.4-3.4	—	7-80	1000-5	0.32-0.40
Thermoplastics, reinforced	2-50	—	20-120	10-1	—
Thermosets	3.5-17	—	35-170	0	0.34
Boron fibers	380	—	3500	0	—
Carbon fibers	275-415	—	2000-5300	1-2	—
Glass fibers (S, E)	73-85	—	3500-4600	5	—
Kevlar fibers (29, 49, 129)	70-113	—	3000-3400	3-4	—
Spectra fibers (900, 1000)	73-100	—	2400-2800	3	—

Note: In the upper table, the lowest values for E, Y, and UTS and the highest values for elongation are for the pure metals. Multiply GPa by 145,000 to obtain psi, and MPa by 145 to obtain psi. For example 100 GPa = 14,500 ksi, and 100 MPa = 14,500 psi.

TABLE 2.1 Typical mechanical properties of various materials at room temperature. See also Tables 10.1, 10.4, 10.8, 11.3 and 11.7.

Manufacturing Processes for Engineering Materials, 5th ed.
Kalpakjian • Schmid

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Power Law Flow Rule

Material	K (MPa)	n
Aluminum, 1100-O	180	0.20
2024-T4	690	0.16
5052-O	210	0.13
6061-O	205	0.20
6061-T6	410	0.05
7075-O	400	0.17
Brass, 7030, annealed	895	0.49
85-15, cold rolled	580	0.34
Bronze (phosphor), annealed	720	0.46
Cobalt-base alloy, heat treated	2070	0.50
Copper, annealed	315	0.54
Molybdenum, annealed	725	0.13
Steel, low carbon, annealed	530	0.26
1045 hot rolled	965	0.14
1112 annealed	760	0.19
1112 cold rolled	760	0.08
4135 annealed	1015	0.17
4135 cold rolled	1100	0.14
4340 annealed	640	0.15
17-4 P-H, annealed	1200	0.05
52100, annealed	1450	0.07
304 stainless, annealed	1275	0.45
410 stainless, annealed	960	0.10

Note: 100 MPa = 14,500 psi.

Flow rule:

$$\sigma = K\varepsilon^n$$

K = Strength coefficient

n = Strain hardening exponent

(measures the ability of a metal to harden)

Typical values for K and n at room temperature.

Manufacturing Processes for Engineering Materials, Kalpakjian • Schmid

ISBN No. 0-13-227271-7

$$\sigma = K\,(\varepsilon_p)^n \tag{5.8}$$

where K is the strength coefficient (stress intercept at $\varepsilon_p = 1$) and n is the strain hardening exponent (slope of the line). The total true strain is then given by

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{1/n} \tag{5.9}$$

This type of true stress–true strain relationship is often referred to as the "Ramberg-Osgood relationship." The value of n gives a measure of the material's work hardening behavior and is usually between 0 and 0.5. Values of K

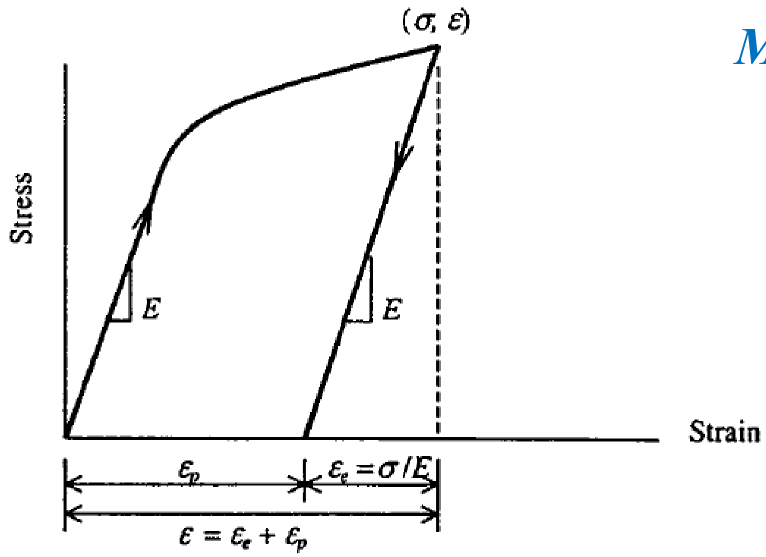


Figure 5.2 Inelastic loading followed by elastic unloading.

Metal Fatigue in Engineering; *2nd ed., R.I. Stephens, A. Fatemi, R.R. Stephens, H.O. Fuchs, 2001.*

[در اين رابطه در واقع كرنش منطقه پلاستيک قرار مى گيرد نه كرنش كل (مجموع الاستيک و پلاستيک) اما از آنجايى كه كرنش الاستيک در مقابل پلاستيک بسيار ناچيز است، معمولا تاثير آنرا ناديده گرفته و رابطه بصورت كلى نوشته مى شود.]

Work Hardening

Dislocations interact with each other and assume configurations that restrict the movement of other dislocations. As the dislocation density increases there is an increase in the flow stress of the material.

The dislocations can be either “strong” or “weak” obstacles to the movement of other dislocations, depending upon the types of interactions that occurs between moving dislocations.

Work hardening or strain hardening can de described as the strengthening of the material by low temperature plastic deformation.

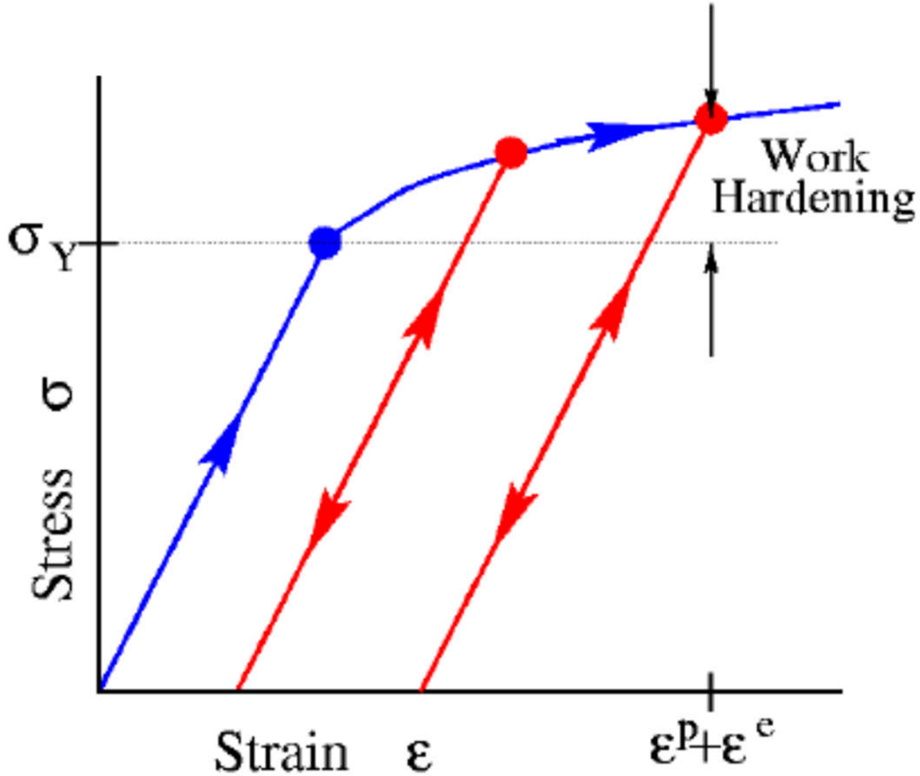


TABLE 6.4. Strength of metals and metal alloys

Low yield strength (0–250 MPa)	Annealed pure metals Mild steels Non-heat-treatable Al–Mg alloys	پرکاربرد - اغلب پلیمرها، بسیاری از کامپوزیت ها، فلزات FCC آنیل شده
Medium yield strength (250–750 MPa)	Heat-treatable 2xxx/7xxx Al alloys High strength structural steels Engineering steels Commercially pure (CP) titanium Stainless steels	پرکاربرد
High yield strength (750–1500 MPa)	Titanium alloys Cu–2% Be precipitation hardened Medium-carbon low alloy steels High strength low alloy steels Precipitation hardened stainless steels	خواص مکانیکی بالا، تولید کم، گران قیمت
Ultra-high yield strength (>1500 MPa)	Maraging steels Patented wire Tool steels	

Mild steel: Fe – C ($\leq$ 0.25) – {Si, Mn, P, S}

- فولاد آرام، ارزان قیمت، فرایند تولید ساده، در برابر تغییر فرم مقاومت چندانی ندارند، مقاومت به خوردگی بسیار بد (نیاز به پوشش)
- Main prop. : جوش پذیری بسیار خوب (عناصر کاربیدزا برای جوشکاری مضر هستند)، شکل پذیری مناسب (تقریبا خالص هستند)، ارزان
- در این فولادها عموماً استحکام معیار .Main prop و حتی Backup نیست.
- فولادهای ساده کربنی قابلیت ماشینکاری خوبی ندارند مگر modify شوند. Machinability: قابلیت براده برداری راحت
- برای بهبود شکل پذیری باید modify شوند مثلا DDQ (Deep Draw Quality)

The need for strength to supplement some other more important property frequently involves conflict because it often happens that any attempt to increase Strength diminishes the major property. There are many examples, as follows:

- Formability
- Machinability
- Wear resistance
- Electrical conductivity

Machinability

- Generally, machining becomes more difficult as strength increases [**but not always**].
- Many small and intricate lightly loaded parts such as cycle components, screws, nuts and gears are machined from bar-stock of steel or other materials in high-speed automatic lathes.
- **This material needs to have its machinability enhanced by additions such as sulphur (to form manganese sulphide in steel, MnS) or lead (in steel, aluminium alloy or brass).**
- Although these additions tend to embrittle the material to which they are added, this disadvantage is tolerated because of enhanced productivity.
- The inclusions therefore elongate less during production of the stock and this minimizes the adverse effect on mechanical properties and maximizes the improvement in machinability.

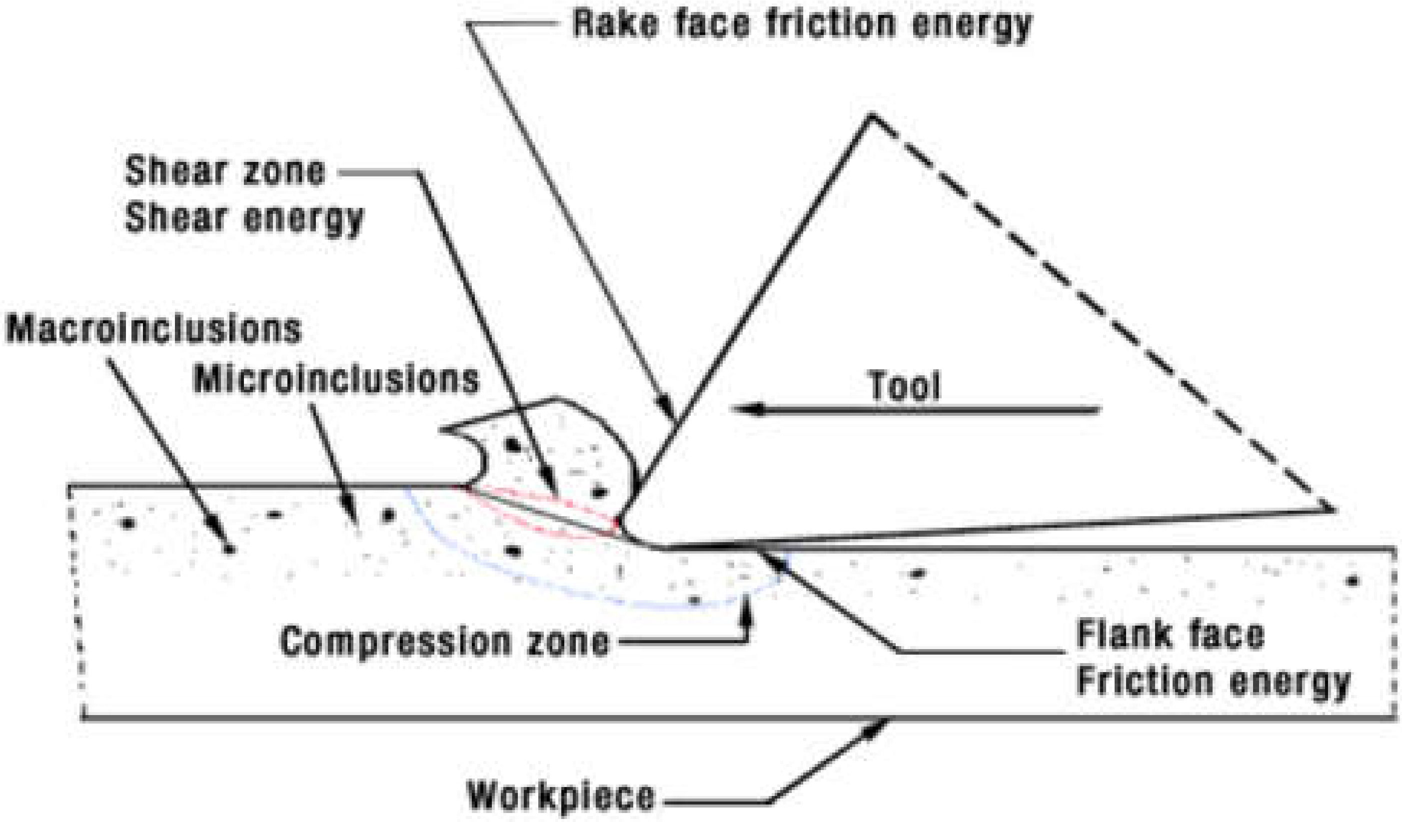


Figure 1: Schematic of a Tool Advancing Through a Metal Part

www.atlasfdry.com/machinability.htm

Electrical conductivity

- The materials which exhibit the highest electrical conductivity are silver, copper and aluminium.
- In each of these materials conductivity is maximized when the material is of highest purity and in the fully annealed condition, a combination which, unfortunately, corresponds to minimum strength.

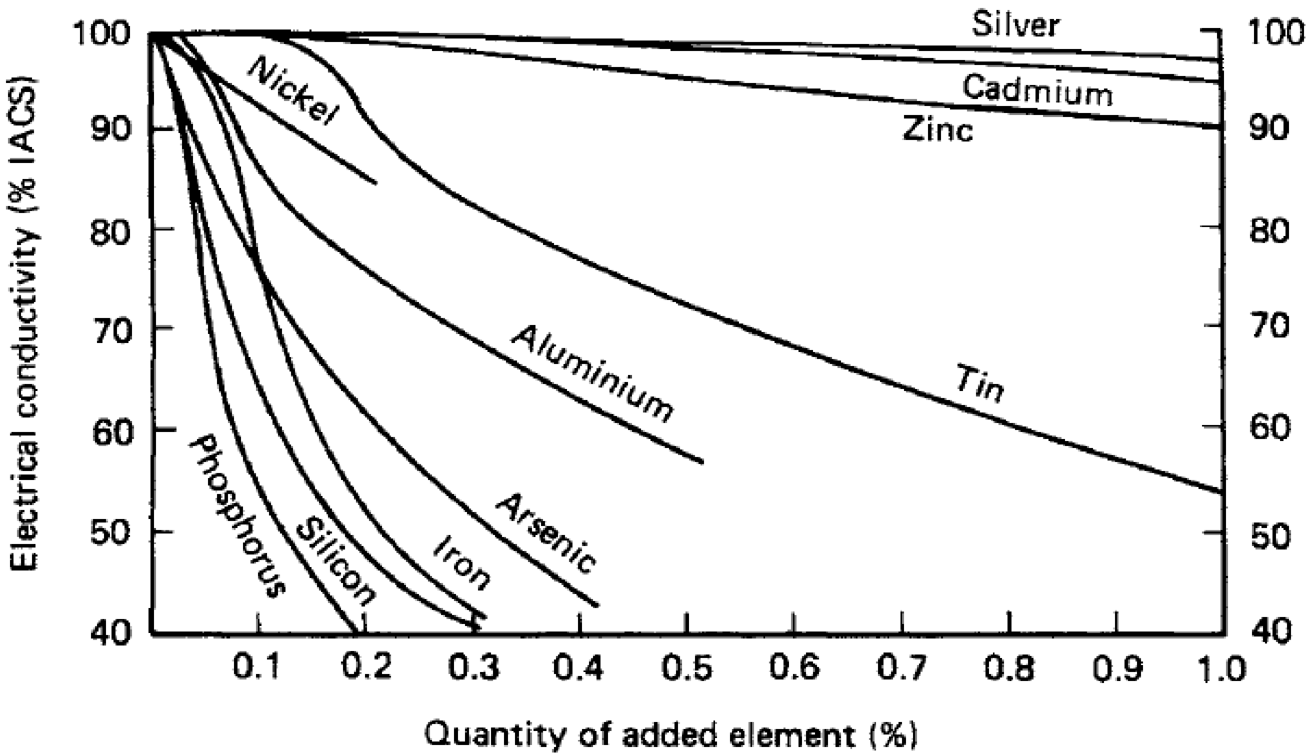


Figure 6.3 Effects of added elements upon the electrical conductivity of copper. (Courtesy: Copper Development Association.[1])

Strength + Conductivity:

Cu-Be

Cu-Cd

Reminder:

Compromising in Materials Selection

TABLE 6.4. Strength of metals and metal alloys

Low yield strength (0–250 MPa)	Annealed pure metals Mild steels Non-heat-treatable Al–Mg alloys	پرکاربرد - اغلب پلیمرها، بسیاری از کامپوزیت ها، فلزات FCC آنیل شده
Medium yield strength (250–750 MPa)	Heat-treatable 2xxx/7xxx Al alloys High strength structural steels Engineering steels Commercially pure (CP) titanium Stainless steels	پرکاربرد
High yield strength (750–1500 MPa)	Titanium alloys Cu–2% Be precipitation hardened Medium-carbon low alloy steels High strength low alloy steels Precipitation hardened stainless steels	خواص مکانیکی بالا، تولید کم، گران قیمت
Ultra-high yield strength (>1500 MPa)	Maraging steels Patented wire Tool steels	

The precipitation hardening (PH) stainless steels are a family of corrosion resistant alloys some of which can be heat treated to provide tensile strengths of **850 to 1700 MPa** and yield strengths of 520 MPa to over 1500 MPa - some three or four times that of an austenitic stainless steel such as type 304 or type 316.

They are used in the oil and gas, nuclear and aerospace industries where a **combination** of high strength, corrosion resistance and a generally low but acceptable degree of toughness is required.

Precipitation hardening is achieved by the addition of **copper, molybdenum, aluminium and titanium** either singly or in combination.

Table 1 Typical Compositions of some commoner precipitation hardening stainless steels

Specification	Common Name	Type	Typical Chemical Analysis %								
			C	Mn	Cr	Ni	Mo	Cu	Al	Ti	Others
A693 Tp630	17/4PH	martensitic	0.05	0.75	16.5	4.25	-	4.25	-	-	Nb 0.3
	FV 520	austenitic-martensitic	0.05	0.6	14.5	4.75	1.4	1.7	-	-	Nb 0.3
A693 Tp631	17/7PH	austenitic-martensitic	0.06	0.7	17.25	7.25	-	-	1.25	-	-
	PH 15/7 Mo	austenitic-martensitic	0.06	0.7	15.5	7.25	2.6	-	1.3	-	-
A 286		austenitic	0.04	1.45	15.25	26.0	1.25	-	0.15	2.15	V 0.25 B 0.007
	JBK 75	austenitic	0.01	0.04	14.75	30.5	1.25	-	0.30	2.15	V 0.25 B 0.0017
	17/10P	austenitic	0.07	0.75	17.2	10.8					P 0.28

TABLE 6.2. Compositions of precipitation-hardened martensitic stainless steels

	C	*Si*	*Mn*	*Cr*	*Ni*	*Mo*	*Cu*	*Nb*	*Al*
FV520B	0.04	0.4	0.5	13.5	5.5	1.6	1.8	0.2	–
PH13-8	0.04	0.03	0.03	12.7	8.2	2.2	–	–	1.1

TABLE 6.3. Properties of maraging steels

	0.2% PS		K_{IC}	
	MPa	ksi	MPa.m$^{1/2}$	ksi.in$^{1/2}$
18Ni–8.5Co–3Mo–Al–Ti	1400	203	110–176	100–160
18Ni–8Co–5Mo–Al–Ti	1700	247	100–165	91–150
18.5Ni–9Co–5Mo–Al–Ti	1900	276	90–100	82–91

❖ ارابه فرود هواپیما (Landing): عموما فولاد **ماریجینگ** (یا آلیاژ تیتانیم یا فولادکرم-نیکل-مولیبدن)

- Heavy duty، چقرمگی (Toughness)، استحکام، خستگی، (جوش پذیری)
- ماریجینگ: استحکام و چقرمگی بسیار بالا، Fe-Ni-Co-Mo-Ti، کربن در حد ناخالصی، امکان فورج و جوشکاری و در پایان aging

Patented Wire:

- The wire is patented by passing through tubes in a furnace at about 970 °C with care to avoid decarburization, giving a uniform large grain size austenite.
- Rapid cooling in air or molten lead follows to a low transformation temperature, so that the final structure is of very fine pearlite with no separation of pro-eutectoid ferrite.
- This structure enables the wire to withstand very large reductions, as compared to annealed material with separated ferrite cells, or tempered martensite where the carbide does not develop into the same fibrous structure.
- The wire is usually worked to tensile strengths in the range **1600-1850 MPa** (232-268 ksi). Patented wire is frequently used for **springs** which can be cold formed and for wire rope for haulage purposes.
- [Music wire; ASTM A228]
- [DIN 17223 part 1, (1.1211) : Patented cold drawn carbon wire for spring]

Because of the relative ease with which the tensile test can be carried out, most strength data for metals are obtained in tension; relative to these, compression data are sparse. However, concrete and ceramics are commonly tested in compression. Plastics, on the other hand are frequently tested in flexure.

For most ductile wrought metallic materials, mechanical properties in compression are sufficiently close to tensile properties as to make no difference for the purposes of materials selection (although there are a few exceptions). In other classes of materials they may be different (Table

TABLE 6.1. Tensile and compressive strengths of materials

	Tensile strength MPa	ksi	*Compressive strength* MPa	ksi
Low-strength grey cast iron	155	22	620	88
High-strength grey cast iron	400	58	1200	174
Portland cement	4	0.6	40	6
Concrete	3	0.5	40	6
Wood	100	15	27	4
Polyether ether ketone (PEEK) + 30% short carbon fibres	233	34	240	35
Epoxy + 50% unidirectional E-glass fibre prepreg laminate –				
parallel to fibres	1100	160	900	130
(perpendicular to fibres)	(40)	(6)	(150)	(22)
Epoxy + 60% unidirectional high strength carbon fibre prepreg laminate –				
parallel to fibres	2000	290	1300	190
(perpendicular to fibres)	(80)	(12)	(250)	(36)

(% by volume)

انتخاب مواد برای کاربردهای

چقرمگی

Toughness

Toughness

- Although strength is traditionally the principal parameter of design, it is not the only, or even the most important property.

- Hardly ever is a material suitable for use if it possesses just one desirable property- usually it must exhibit a suitable *combination of properties*.

- In the case of engineering structures it is important that strength be combined with toughness.

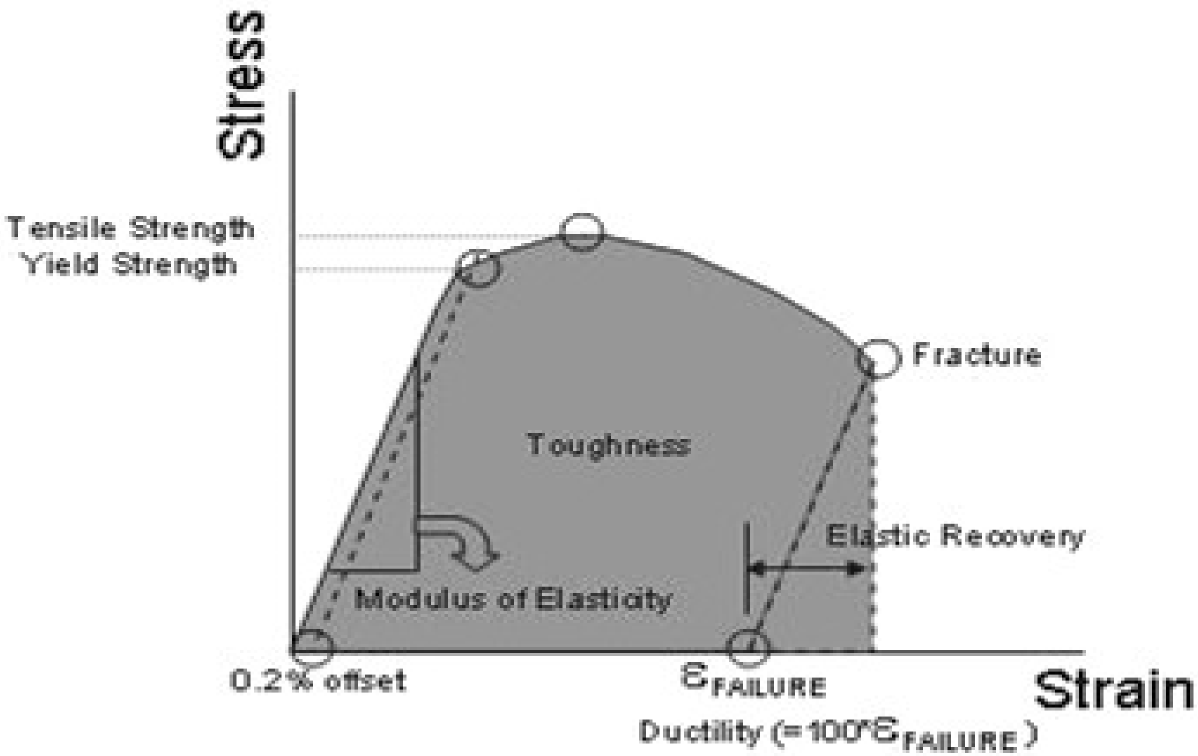
- This is because experience has shown that most service failures at temperatures below the creep range occur not as a result of general plastic distortion but because of fracture at nominal stresses lower than those for general yield.

- ممکن است یک ماده استحکام ایستایی بالایی داشته باشد اما برای بارگذاری های سریع تر از معمول مناسب نباشد.

- اهمیت بیشتر چقرمگی در بارگذاری های دینامیکی و ضربه ای مانند بسیاری از قطعات خودرو، قطعات هواپیما، ...

- Strain rate in static loading ≈ 10^{-3} /s

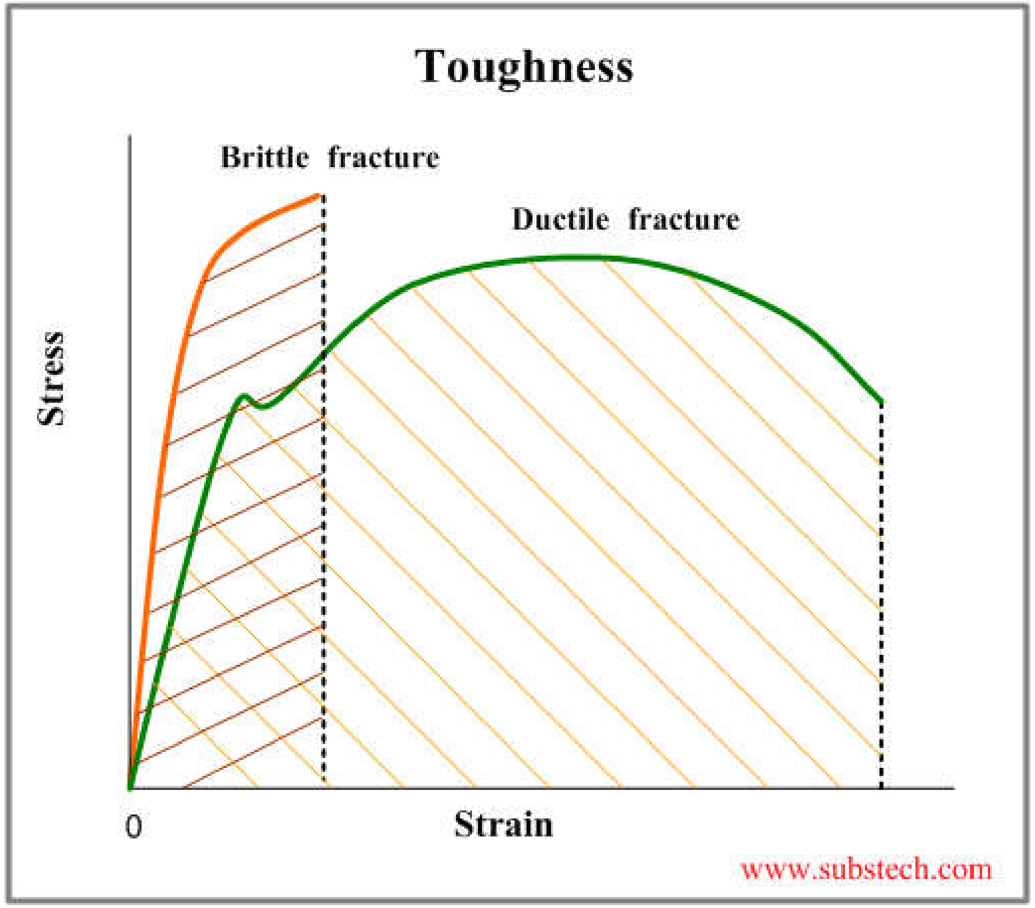
- تست ضربه نمونه ای از بارگذاری دینامیکی (dynamic loading) است که Strain rate >> 10^{-3} /s

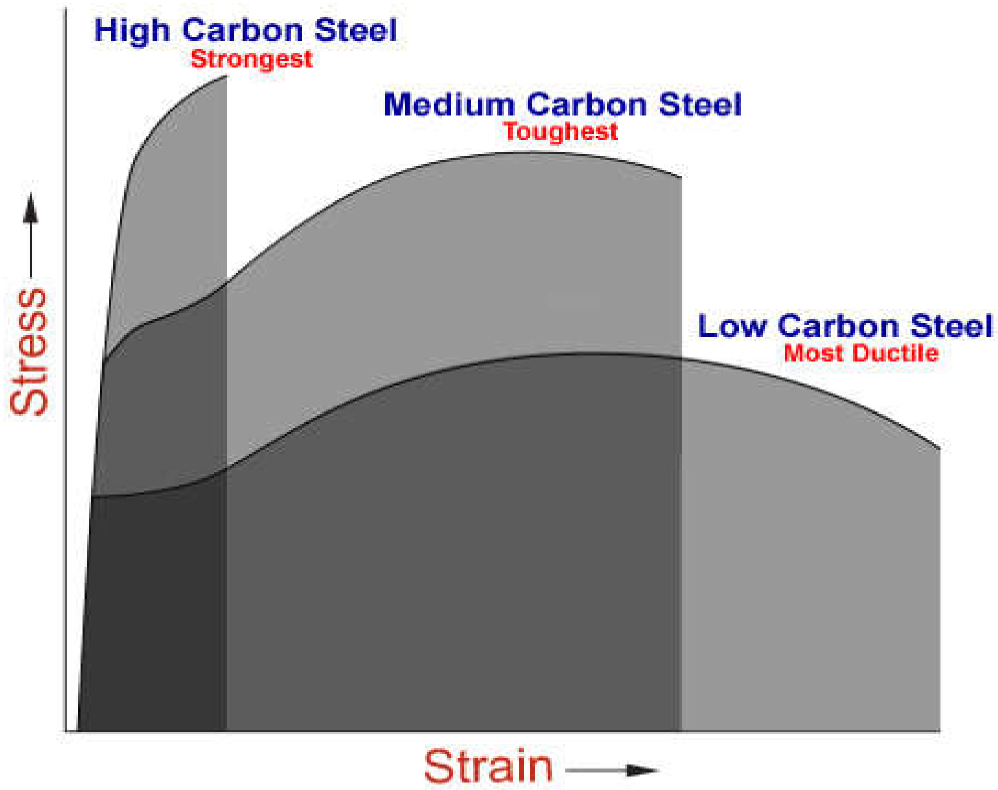


Several variables that have a profound influence on the toughness of a material:

- Strain rate (rate of loading)
- Temperature
- Notch effect [stress state]

A metal may possess satisfactory toughness under static loads but may fail under dynamic loads or impact.





The meaning of toughness

- Toughness is resistance to fracture. Absence of toughness is denoted by the term **brittle** and when a material can be induced to fracture with the expenditure of little effort it is so described.

- The effort expended can be thought of in terms of stress or energy giving different but equally valid ways of looking at the fracture problem, as in the Table . This table shows that **fracture** can also be categorized in terms of the speed with which it propagates.

	Brittle	*Tough*
Stress	Fracture occurs at a level of stress below that required to produce yielding across the whole cross-section	Fracture occurs at a level of stress which corresponds to that required to produce yielding across the whole cross-section
Energy	Fracture is a low-energy process	Fracture is a high-energy process
Speed	Fracture is fast	Fracture is slow

Tests for Evaluating Toughness

- Many tests have been invented to assess the toughness of a material, e.g.:
  - notched tensile test
  - Charpy impact test
  - the drop weight tear test (DWTT)
  - . . .
- The early tests were highly arbitrary and merely attempted to imitate the conditions of service that were known to decrease toughness.
- The toughness of steel is decreased by:
  - decreasing temperature;
  - increasing strain rate; and
  - increasing plastic constraint.

The assessment of toughness

There are two main ways of assessing materials for resistance to fracture:

(1) the transition temperature approach and ⇐ ***Impact Test***

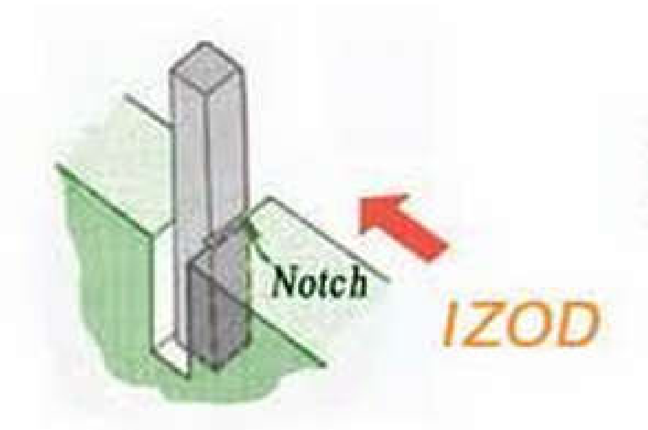
(2) the fracture mechanics approach. ⇐ ***Fracture Mechanics***

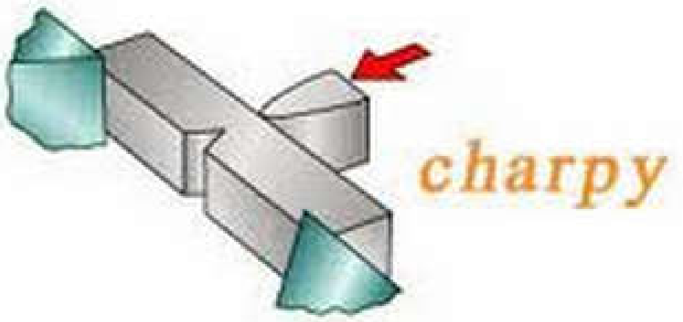
Impact Tests

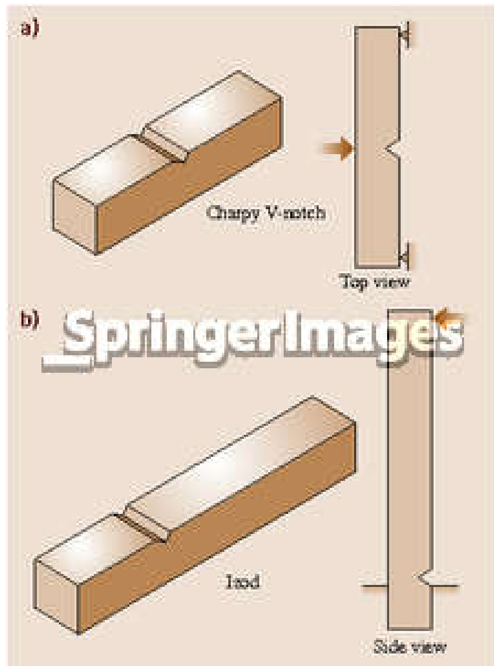
Impact tests are designed to measure the resistance to failure of a material to a suddenly applied force. The test measures the impact energy, or the energy absorbed prior to fracture. Impact energy is a measure of the work done to fracture a test specimen.

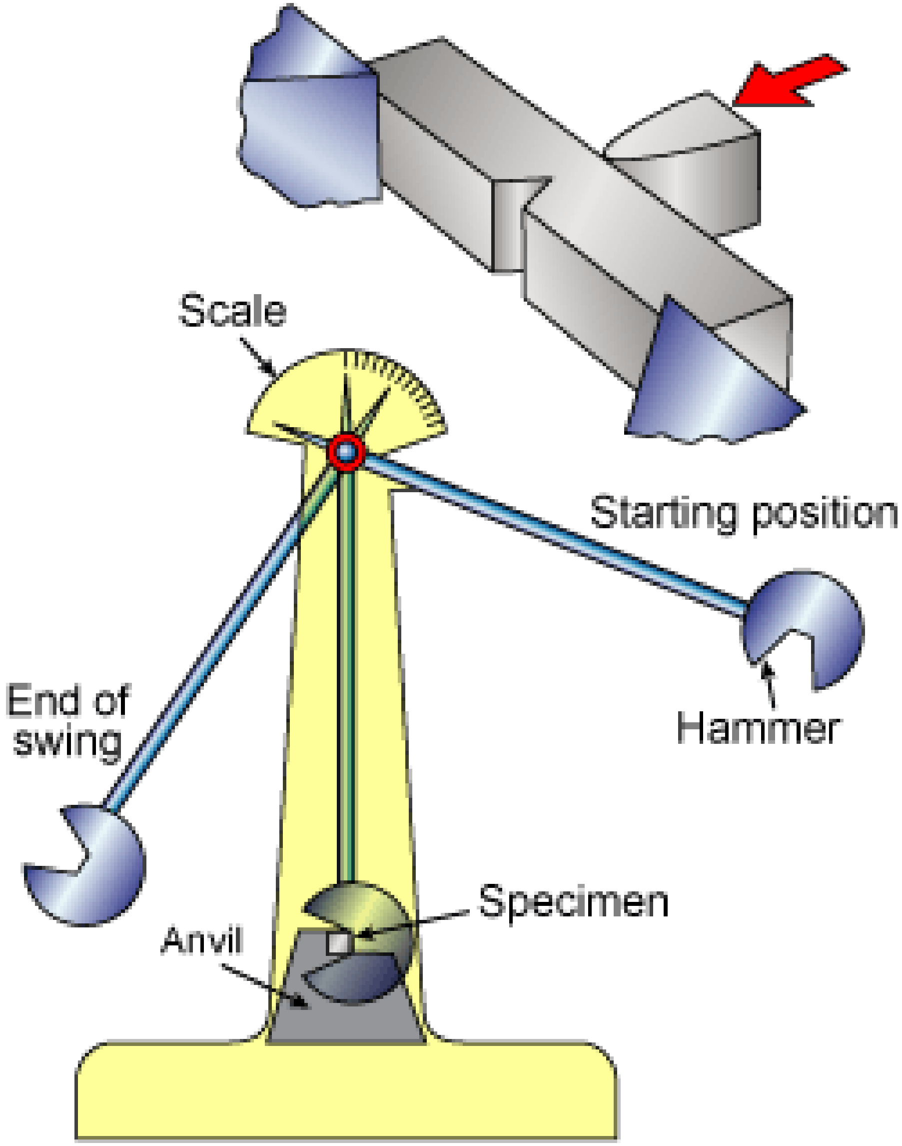
The most common methods of measuring impact energy are the:

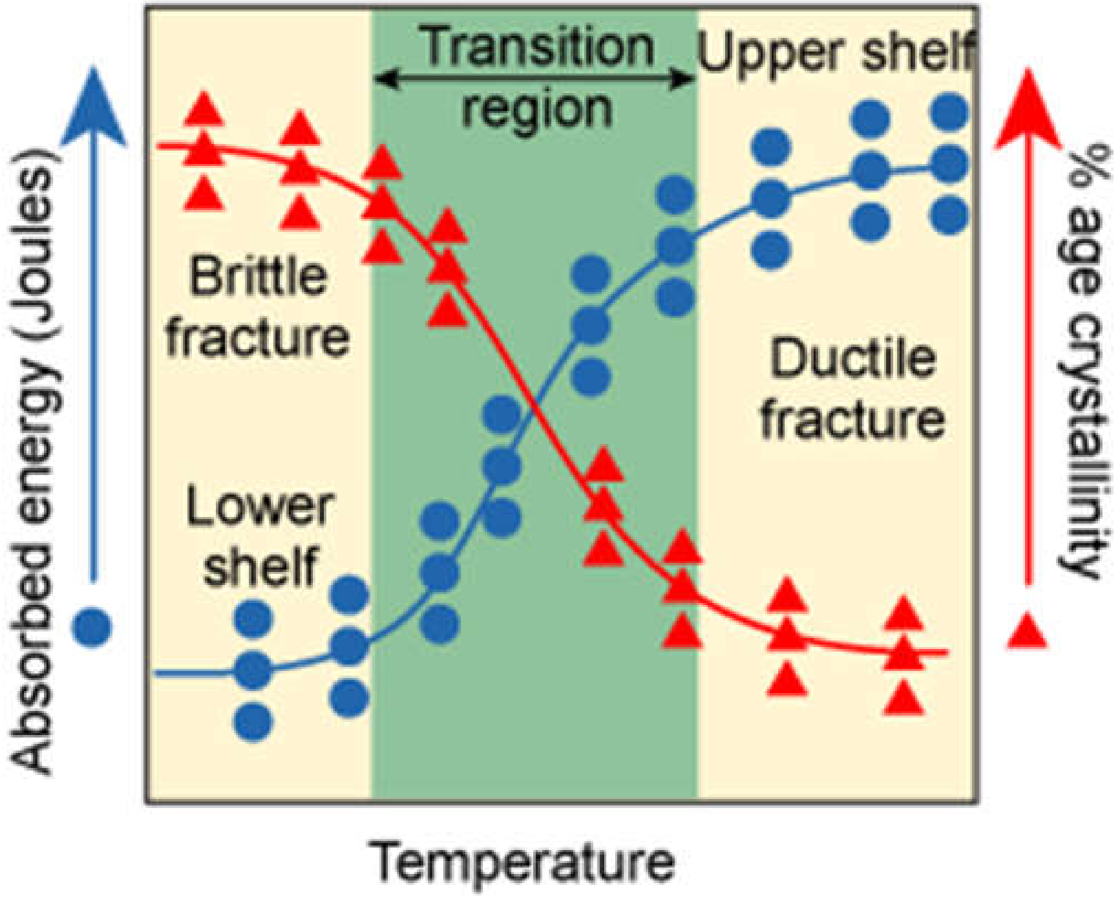
- **Charpy Test**
- **Izod Test**

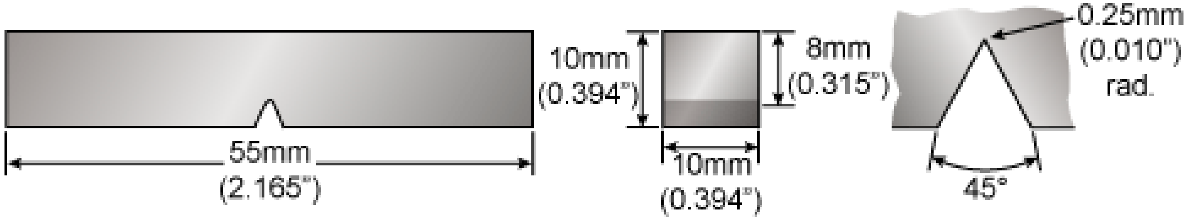


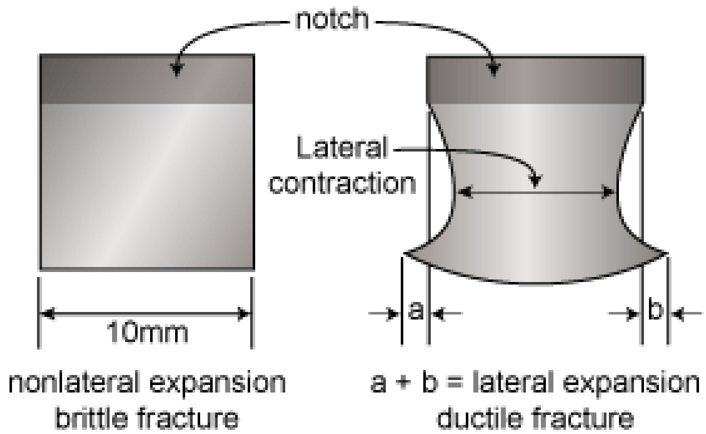





Scale
Starting position
End of swing
Hammer
Specimen
Anvil


Transition region
Upper shelf
Brittle fracture
Lower shelf
Ductile fracture
Absorbed energy (Joules)
% age crystallinity
Temperature


55mm
(2.165")
10mm
(0.394")
10mm
(0.394")
8mm
(0.315")
0.25mm
(0.010")
rad.
45°


notch
Lateral contraction
10mm
a
b
nonlateral expansion
brittle fracture
a + b = lateral expansion
ductile fracture

Energy absorbed

OR

Appearance of fracture

OR

Deformation (lateral expansion)

} **VS** **Temperature**

Fracture appearance is described according to the proportions of the fracture surface which appear crystalline or fibrous. The latter is termed the shear area (SA). Thus: % crystallinity + % SA = 100. Specimens fractured at temperatures close to the transition temperature will show a mixed fracture appearance.

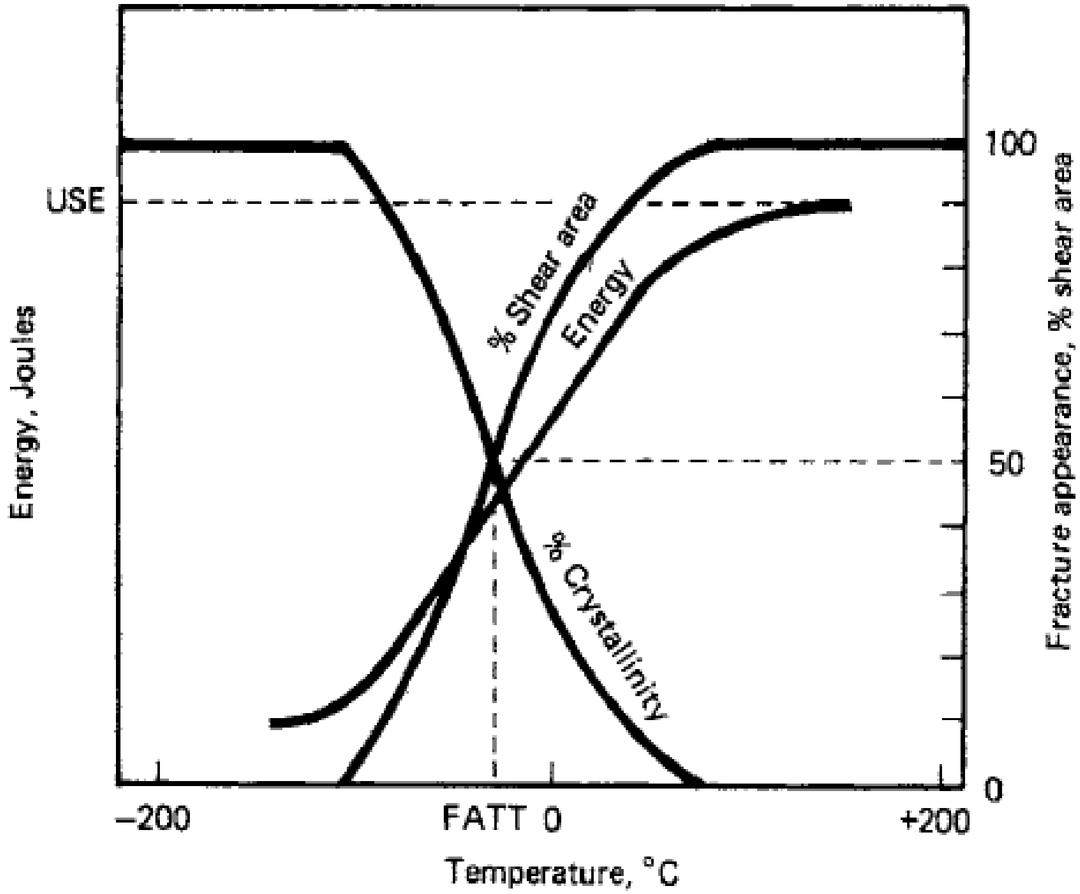
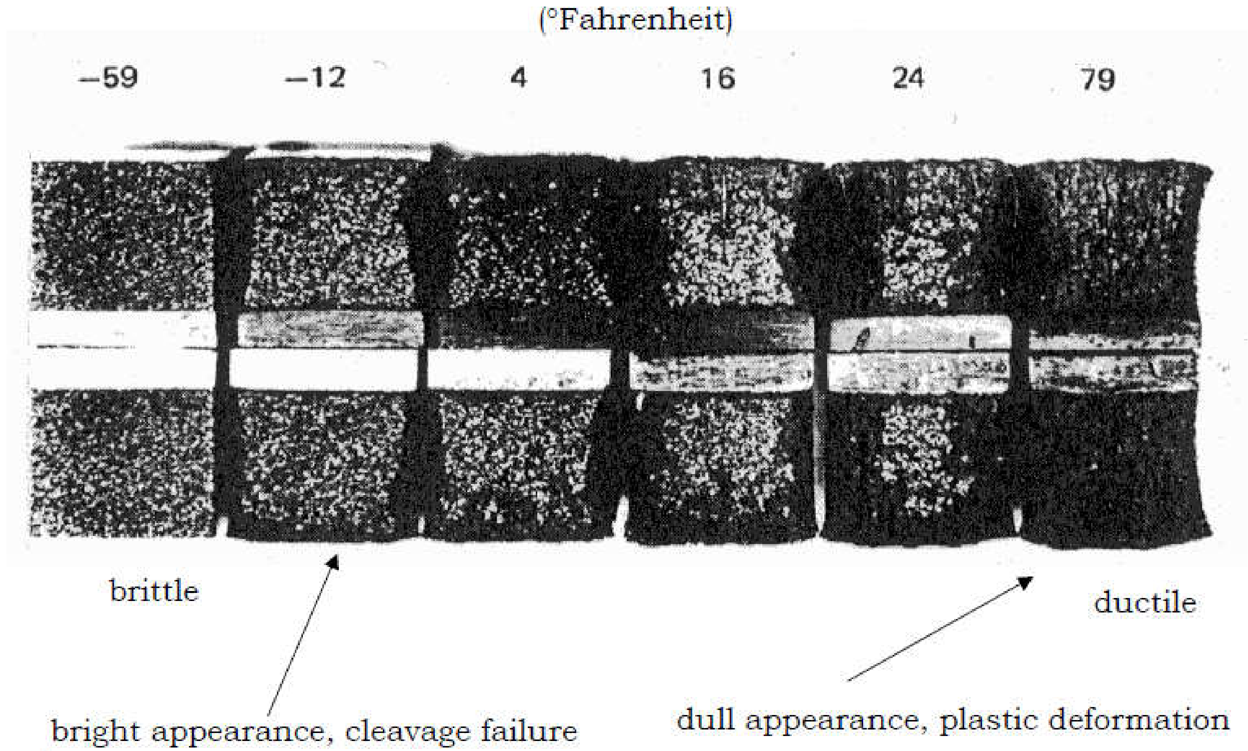
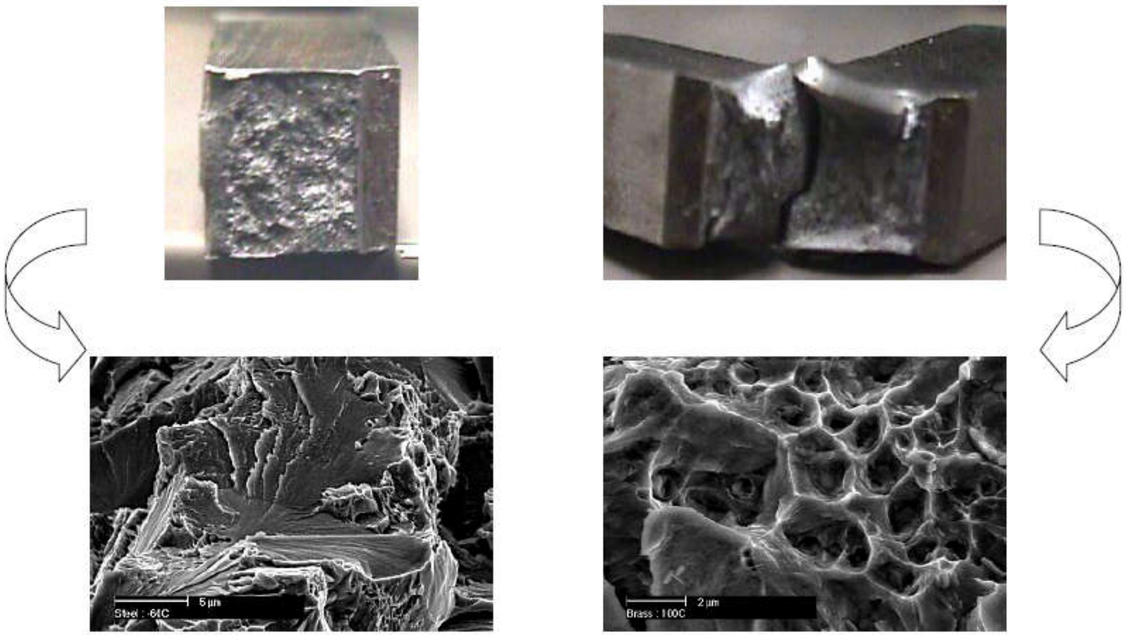


Figure 7.1 Charpy diagram for low-strength steel.



Fracture Surface Microstructure



brittle ductile

A fractured Liberty Ship

Welding, in place of riveted construction, was a novelty in ship building at the time and was initially blamed for the failures. Intensive analysis, however, eventually identified the relatively high DBTT of the steel used for these ships as the root cause. The cold water temperatures of the North Atlantic transformed the normally ductile steel into an extremely brittle material, and single load events ranging from large waves at sea to heavy cargo load placement were sufficient to cause brittle single cycle fractures.

If the transition from brittle to tough behaviour is quite distinct then it is possible to specify a single value of temperature to represent the transition. This transition temperature then gives, for the steel under test, the lower limit of permissible temperature in service. That is to say, if a given steel is to be a candidate material for a given application its measured transition temperature must be lower than the temperature of intended service.

The transition approach fails with high-strength materials because the transition becomes so indistinct as to be almost indeterminate. In terms of energies the upper shelf energy (USE) is not much greater than that at the lower, and the difference is spread over such a wide range of temperatures that the concept of transition temperature has hardly any meaning (Figure 7.2).

It is therefore especially with materials of higher strength (non-ferrous as well as ferrous) that the toughness concepts of fracture mechanics have proved so valuable.

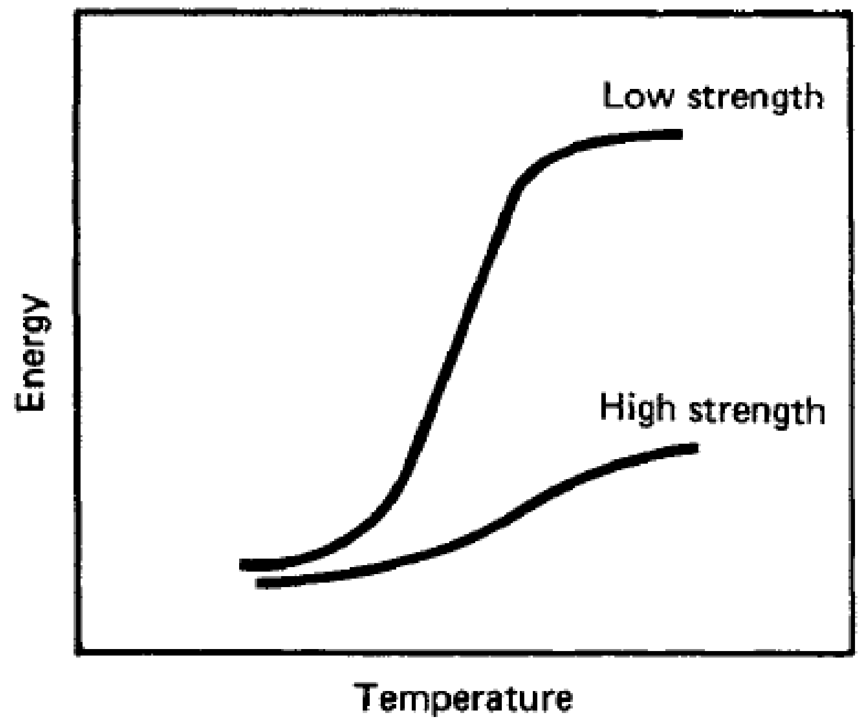
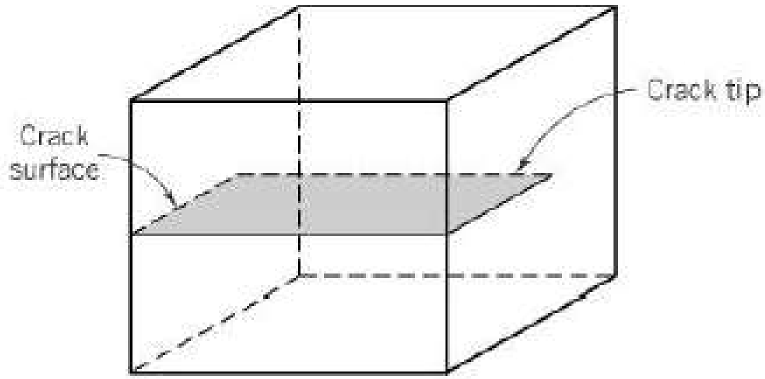


Figure 7.2 Comparison of Charpy energies for low- and high-strength steels.

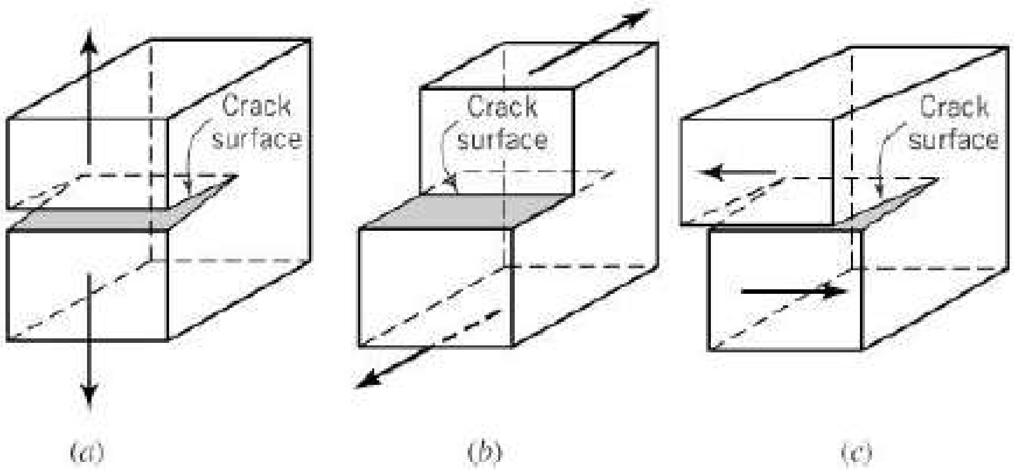
Fracture mechanics

- Crack may propagate in one or more ways as a function of the loading
  - Mode I   Opening Mode
  - Mode II   Sliding Mode
  - Mode III   Tearing Mode



- Most general case is mixed mode

- In isotropic materials, brittle fracture usually occurs in Mode I



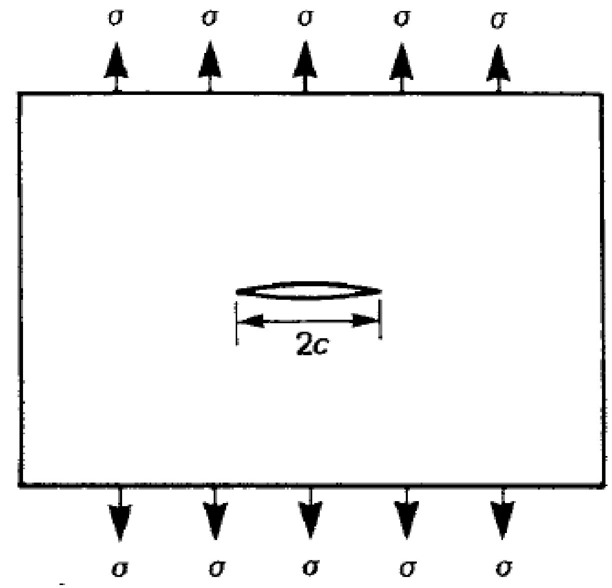
(a) Mode I, (b) Mode II, (c) Mode III

The factor $\sigma\sqrt{\pi c}$ is written K, termed the elastic stress intensity factor. The value of K at propagation of fracture is denoted K_C

$$K_C = \sigma\sqrt{\pi c}$$

K_C is not a material constant since it is determined by geometry, but when the thickness of the specimen is large enough to ensure plane strain conditions K_C has a minimum value for the given material. This is denoted K_{IC}, since crack advancement is then in the opening mode. K_{IC} is therefore a material constant (Figure 7.5). The dimensions of K are stress$\sqrt{}$length and are expressed in MPa m$^{1/2}$ or similar.

ضریب شدت تنش (الاستیکی)



Centre-cracked plate loaded in tension.

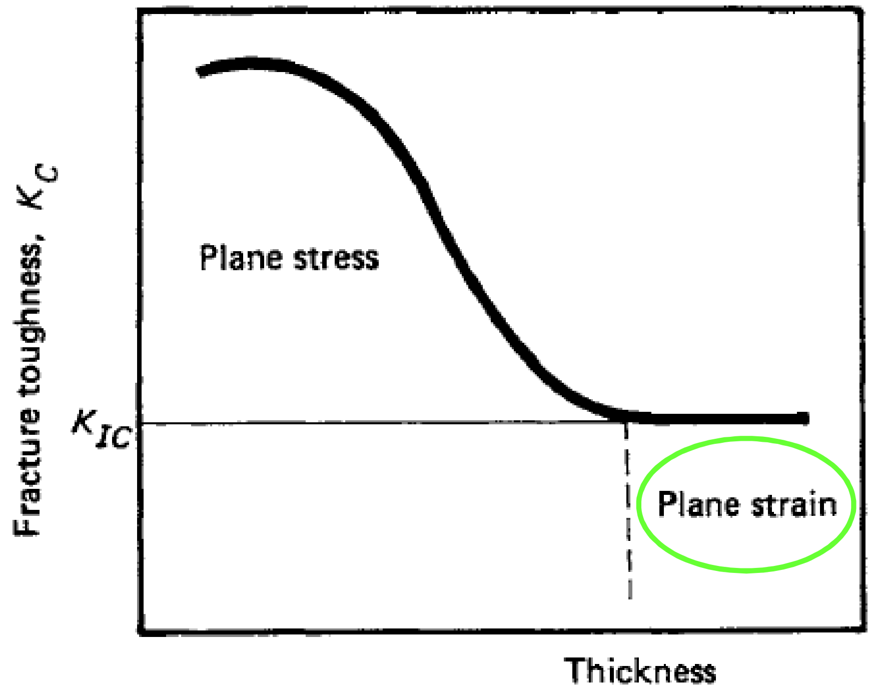
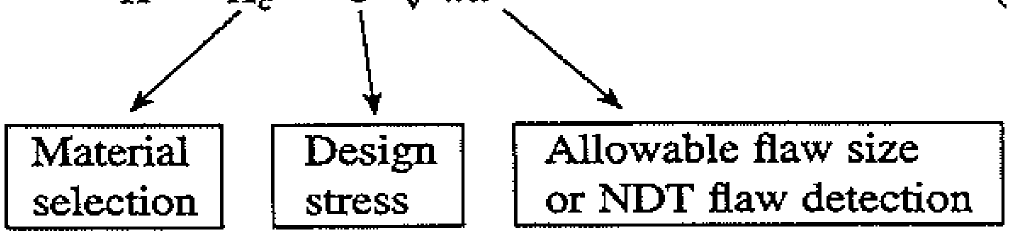


Figure 7.5 Variation of fracture toughness with thickness.

8.3 DESIGN PHILOSOPHY

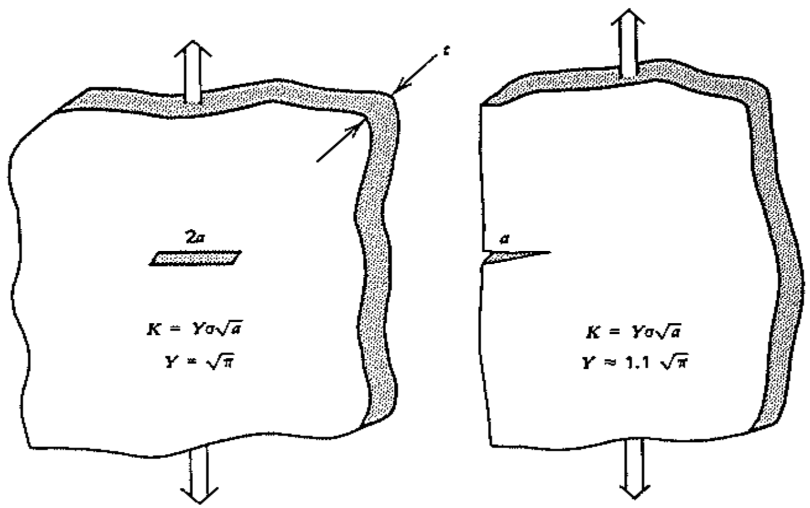
The interaction of material properties, such as the fracture toughness, with the design stress and crack size controls the conditions for fracture in a component. For example, it is seen from Fig. 8.7a that the fracture condition for an infinitely large cracked plate would be

$$K = K_c = \sigma\sqrt{\pi a} \tag{8-28}$$



This relation may be used in one of several ways to design against a component failure. For example, if you are to build a system that must withstand the ravages of a liquid metal environment, such as in some nuclear reactors, one of your major concerns is the selection of a suitable corrosion-resistant material. Once done, you have essentially fixed K_c. In addition, if you allow for the presence of a relatively large stable crack—one that can be readily detected and repaired—the design stress is fixed and must be less than $K_c/\sqrt{\pi a}$.

(Hertzberg)



(a) (b)

$$K = \alpha\,\sigma\sqrt{\pi a} \qquad ,(Y = \alpha\,, a = c)$$

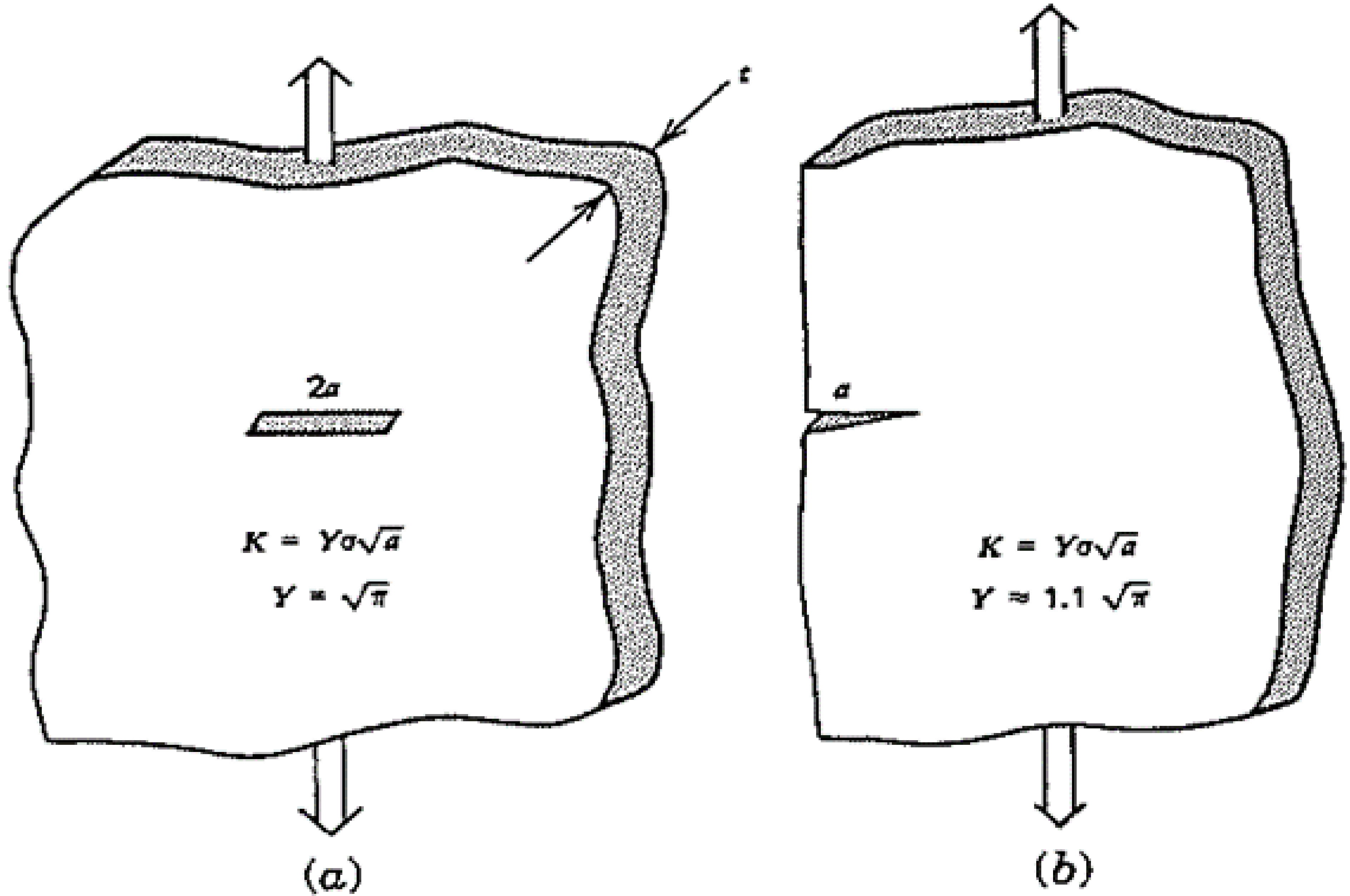

t
2a
K = Yσ√a
Y = √π
a
K = Yσ√a
Y ≈ 1.1 √π
(a)
(b)

Table 1: Stress intensity factors for several common geometries.

Type of Crack	Stress Intensity Factor, K_I
Center crack, length $2a$, in an infinite plate	$\sigma_\infty \sqrt{\pi a}$
Edge crack, length a, in a semi-infinite plate	$1.12\ \sigma_\infty \sqrt{\pi a}$
Central penny-shaped crack, radius a, in in infinite body	$2\ \sigma_\infty \sqrt{\frac{a}{\pi}}$
Center crack, length $2a$ in plate of width W	$\sigma_\infty \sqrt{W \tan\left(\frac{\pi a}{W}\right)}$
2 symmetrical edge cracks, each length a, in plate of total width W	$\sigma_\infty \sqrt{W \left[\tan\left(\frac{\pi a}{W}\right) + 0.1 \sin\left(\frac{2\pi a}{W}\right)\right]}$

رابطه کلی:

$$K = Y\sigma\sqrt{\pi a}$$

Materials selection for toughness

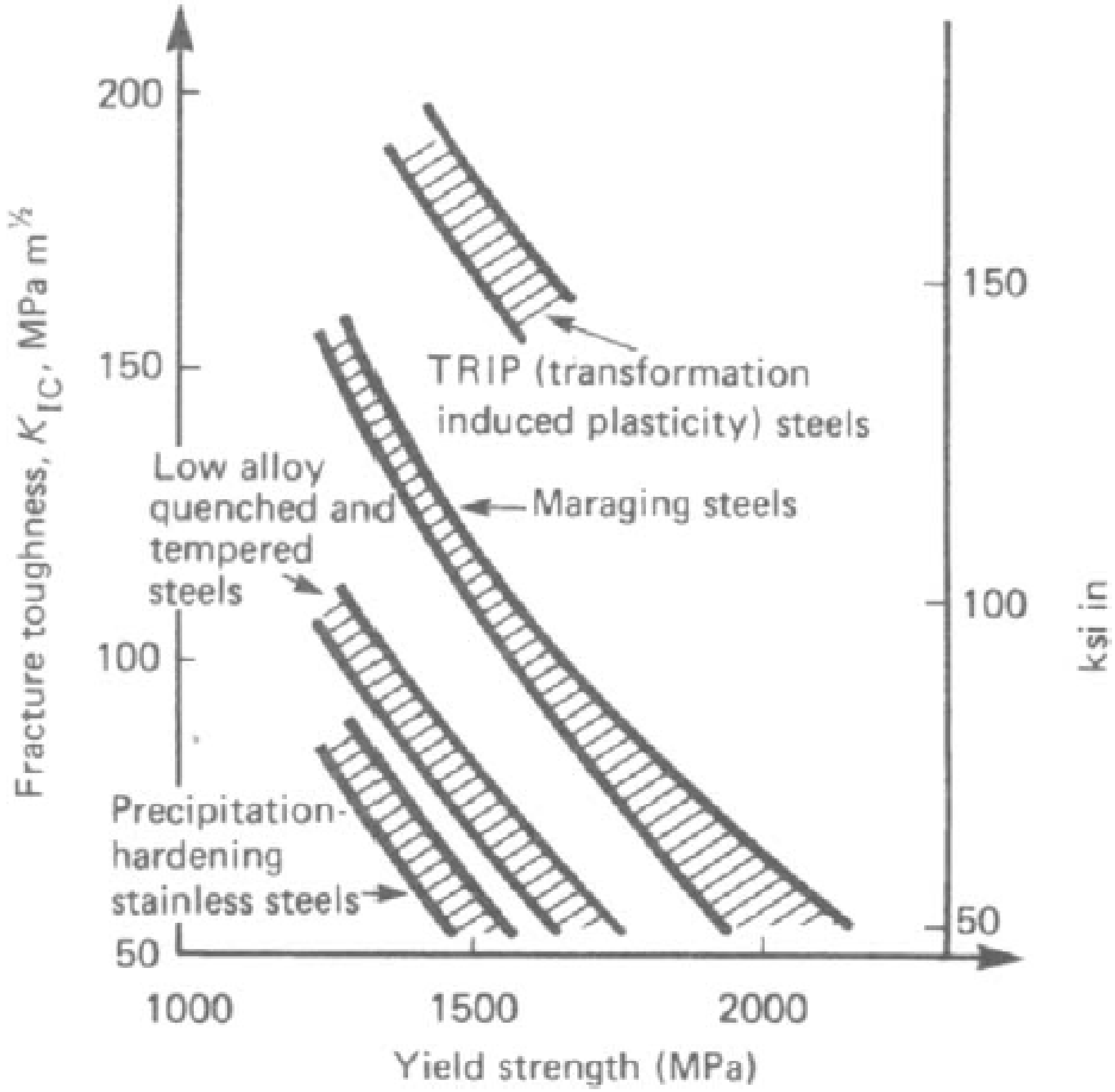


Figure 7.7 Variation of fracture toughness with yield strength for various classes of high-strength steels. (From J. F. Knott.)[8]

TABLE 7.4. Typical values of plane strain fracture toughness K_{IC}

	Strength		Fracture toughness	
	MPa	ksi	$MPa\ m^{1/2}$	$ksi\ in^{1/2}$
Steels				
Medium-carbon steel	260	37.7	54	49
Pressure-vessel steel A533B Q and T	500	72.5	200	182
Maraging steel	1390	202	110–176	100–160
	1700	247	99–165	90–150
	1930	280	85–143	80–130
300M	2033	295	66	60
	1895	275	83	75
AISI 4340	1758	255	77	70
	1930	280	61	55
AISI 4340				
Tempered 200°C, commercial purity	1650	239	40	36
Tempered 200°C, high purity	1630	236	80	73
Aluminium alloys				
2024–T4	346	50	55	50
2024–T851	414	60	24	22
7075–T6	463	67	38–66	35–60
7075–T651	482	70	31	28
7178–T6	560	81	23	21
7178–T651	517	75	24	22
Titanium alloys				
Ti–6Al–4V	830	120	50–60	45–55
Ti-6Al–5Zr–0.5Mo–0.2Si	877	127	60–70	55–65
Ti–4Al–4Mo–2Sn–0.5Si	960	139	40–50	36–45
Ti–11Sn–5Zr–2.25Al–1Mo–0.2Si	970	141	35–45	32–41
Ti–4Al–4Mo–4Sn–0.5Si	1095	159	30–40	27–36
Thermoplastics				
PMMA	30	4	1	0.9
GP Polystyrene	–	–	1	0.9
Acrylic sheet	–	–	2	1.8
Polycarbonate	–	–	2.2	2.0
Others				
Concrete	–	–	0.3–1.3	0.3–1.2
Glass	–	–	0.3–0.6	0.3–0.5
Dense alumina			2.5–3	2.3–2.7
Zirconia toughened alumina			6–12	5.5–11.0
Partially stabilized zirconia			8–16	7.3–14.6
Douglas fir	–	–	0.3	0.3

$$K_{IC} = \alpha \left({}^{\sigma_{ys}}/_{f} \right) \sqrt{\pi a_c}$$

$$\frac{f^2}{\pi}\left[\frac{K_{IC}}{\sigma_{YS}}\right]^2.$$

The final column gives the critical crack length for a stress equal to half the yield stress (i.e. $f = 2$).

TABLE 7.5

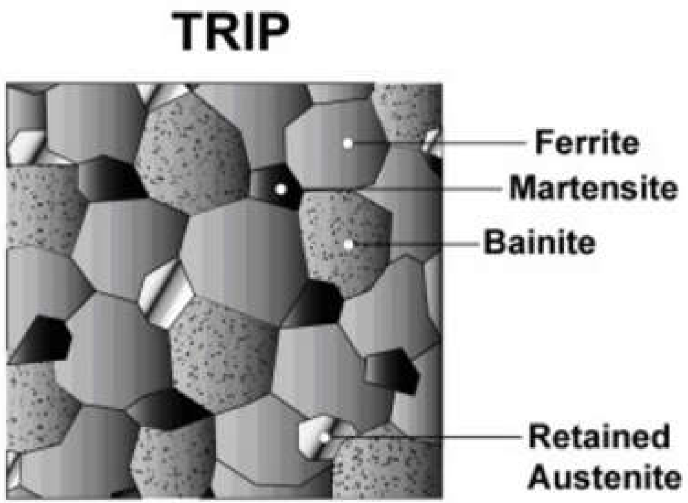
Steel	*Structure*	σ_{YS}		K_{IC}		$4/\pi[K_{IC}/\sigma_{YS}]^2$	
		MPa	ksi	MPa m$^{1/2}$	ksi in$^{1/2}$	mm	in
A212	Ferrite-pearlite	283	41	77	70	94	3.7
A533	Mixed transformation products	427	62	95	86	63	2.5
A543	Lower bainite	586	85	181	165	121	4.8

- موادی مناسب تر هستند که استحکام، K_{IC} و طول ترک بحرانی آنها همزمان بالا باشد.
- در حالت کلی فولادهای آلیاژی از لحاظ تافنس، بهترین شرایط را دارند.

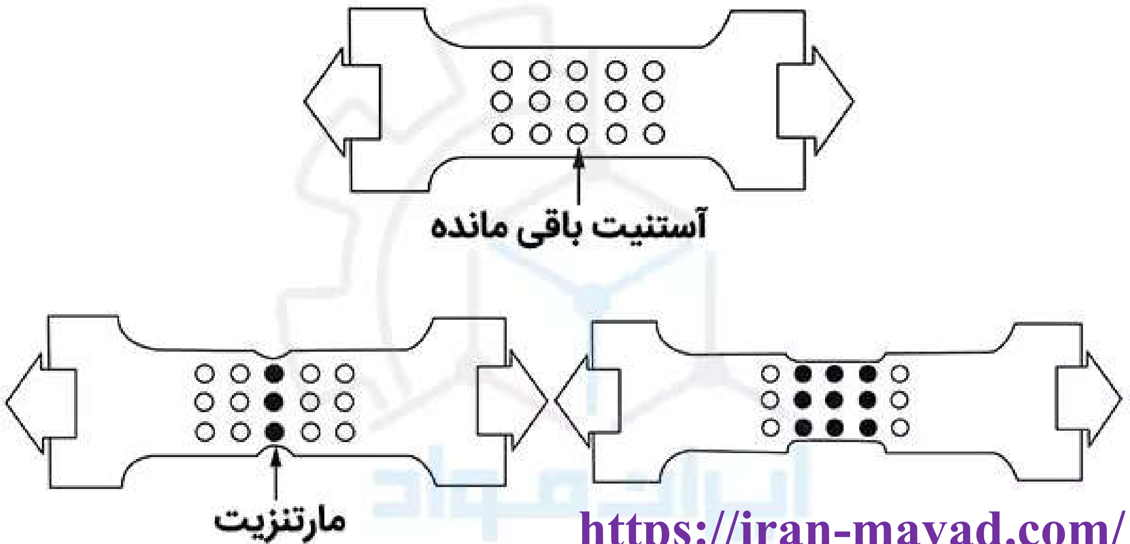
Optional

Transformation-Induced Plasticity (TRIP) Steel

The microstructure of TRIP steels is retained austenite embedded in a primary matrix of ferrite. In addition to a minimum of five volume percent of retained austenite, hard phases such as martensite and bainite are present in varying amounts. TRIP steels typically require the use of an isothermal hold at an intermediate temperature, which produces some bainite. The higher silicon and carbon content of TRIP steels also result in significant volume fractions of retained austenite in the final microstructure.



Bainite and retained austenite are additional phases in TRIP



TRIP steel

Optional

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From Wikipedia, the free encyclopedia

TRIP steel are a class of high-strength steel alloys typically used in naval and marine applications and in the automotive industry.[1] TRIP stands for "Transformation induced plasticity," which implies a phase transformation in the material, typically when a stress is applied. These alloys are known to possess an outstanding combination of strength and ductility.

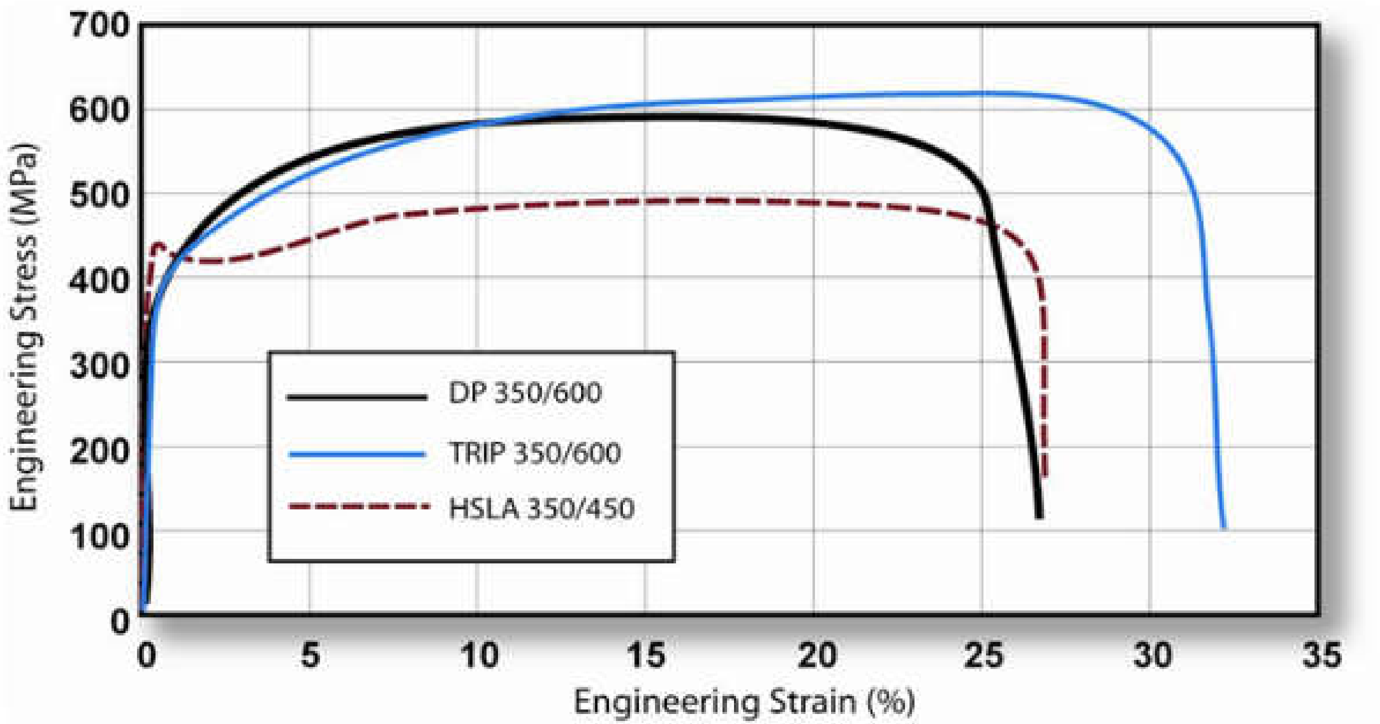
Microstructure [edit]

TRIP steels possess a microstructure consisting of austenite with sufficient thermodynamic instability such that transformation to martensite is achieved during loading or deformation. Many automotive TRIP steels possess retained austenite within a ferrite matrix, which may also contain hard phases like bainite and martensite.[2] In the case of these alloys, the high silicon and carbon content of TRIP steels results in significant volume fractions of retained austenite in the final microstructure.

TRIP steels use higher quantities of carbon than dual-phase steels to obtain sufficient carbon content for stabilizing the retained austenite phase to below ambient temperature. Higher contents of silicon and/or aluminium accelerate the ferrite/bainite formation. They are also added to avoid formation of carbide in the bainite region.

Optional

During deformation, the dispersion of hard second phases in soft ferrite creates a high work hardening rate, as observed in the DP steels. However, in TRIP steels the retained austenite also progressively transforms to mart with increasing strain, thereby increasing the work hardening rate at higher strain levels. This is illustrated in Figure 2-8, where the engineering stress-strain behavior of HSLA, DP and TRIP steels of approximately similar yield strengths are compared. The TRIP steel has a lower initial work hardening rate than the DP steel, but the hardening rate persists at higher strains where work hardening of the DP begins to diminish. Additional engineering and true stress-strain curves for TRIP steel grades are located in Figure 2-9 of the Advanced High-Strength Steels Application Guidelines.



The work hardening rates of TRIP steels are substantially higher than for conventional HSS, providing significant stretch forming. This is particularly useful when designers take advantage of the high work hardening rate (and increased bake hardening effect) to design a part utilizing the as-formed mechanical properties. The high work hardening rate persists to higher strains in TRIP steels, providing a slight advantage over DP in the most severe stretch forming applications.

TRIP steels use higher quantities of carbon than DP steels to obtain sufficient carbon content for stabilizing the retained austenite phase to below ambient temperature. Higher contents of silicon and/or aluminium accelerate the ferrite/bainite formation. These elements assist in maintaining the necessary carbon content within the retained austenite. Suppressing the carbide precipitation during bainitic transformation appears to be crucial for TRIP steels. Silicon and aluminium are used to avoid carbide precipitation in the bainite region.

Wikipedia
The Free Encyclopedia

Optional

High-strength low-alloy steel

From Wikipedia, the free encyclopedia

High-strength low-alloy steel (**HSLA**) is a type of alloy steel that provides better mechanical properties or greater resistance to corrosion than carbon steel. HSLA steels vary from other steels in that they are not made to meet a specific chemical composition but rather to specific mechanical properties. They have a carbon content between 0.05–0.25% to retain formability and weldability. Other alloying elements include up to 2.0% manganese and small quantities of copper, nickel, niobium, nitrogen, vanadium, chromium, molybdenum, titanium, calcium, rare earth elements, or zirconium.[1][2] Copper, titanium, vanadium, and niobium are added for strengthening purposes.[2] These elements are intended to alter the microstructure of carbon steels, which is usually a ferrite-pearlite aggregate, to produce a very fine dispersion of alloy carbides in an almost pure ferrite matrix. This eliminates the toughness-reducing effect of a pearlitic volume fraction yet maintains and increases the material's strength by refining the grain size, which in the case of ferrite increases yield strength by 50% for every halving of the mean grain diameter. Precipitation strengthening plays a minor role, too. Their yield strengths can be anywhere between 250–590 megapascals (36,000–86,000 psi). Because of their higher strength and toughness HSLA steels usually require 25 to 30% more power to form, as compared to carbon steels.[2]

SAE HSLA steel grade compositions[7]

Grade	% Carbon (max)	% Manganese (max)	% Phosphorus (max)	% Sulfur (max)	% Silicon (max)	Notes
942X	0.21	1.35	0.04	0.05	0.90	Niobium or vanadium treated
945A	0.15	1.00	0.04	0.05	0.90	
945C	0.23	1.40	0.04	0.05	0.90	
945X	0.22	1.35	0.04	0.05	0.90	Niobium or vanadium treated
950A	0.15	1.30	0.04	0.05	0.90	
950B	0.22	1.30	0.04	0.05	0.90	
950C	0.25	1.60	0.04	0.05	0.90	
950D	0.15	1.00	0.15	0.05	0.90	
950X	0.23	1.35	0.04	0.05	0.90	Niobium or vanadium treated
955X	0.25	1.35	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
960X	0.26	1.45	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
965X	0.26	1.45	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
970X	0.26	1.65	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated
980X	0.26	1.65	0.04	0.05	0.90	Niobium, vanadium, or nitrogen treated

Optional

https://en.wikipedia.org/wiki/High-strength_low-alloy_steel

High-strength low-alloy steel

Wikipedia
The Free Encyclopedia

From Wikipedia, the free encyclopedia

Classifications [edit]

- **Weathering steels**: steels which have better corrosion resistance. A common example is COR-TEN.
- **Control-rolled steels**: hot rolled steels which have a highly deformed austenite structure that will transform to a very fine equiaxed ferrite structure upon cooling.
- **Pearlite-reduced steels**: low carbon content steels which lead to little or no pearlite, but rather a very fine grain ferrite matrix. It is strengthened by precipitation hardening.
- **Acicular ferrite steels**: These steels are characterized by a very fine high strength acicular ferrite structure, a very low carbon content, and good hardenability.
- **Dual-phase steels**: These steels have a ferrite microstruture that contain small, uniformly distributed sections of martensite. This microstructure gives the steels a low yield strength, high rate of work hardening, and good formability.[1]
- **Microalloyed steels**: steels which contain very small additions of niobium, vanadium, and/or titanium to obtain a refined grain size and/or precipitation hardening.

A common type of micro-alloyed steel is improved-formability HSLA. It has a yield strength up to 80,000 psi (550 MPa) but only costs 24% more than A36 steel (36,000 psi (250 MPa)). One of the disadvantages of this steel is that it is 30 to 40% less ductile. In the U.S., these steels are dictated by the ASTM standards A1008/A1008M and A1011/A1011M for sheet metal and A656/A656M for plates. These steels were developed for the automotive industry to reduce weight without losing strength. Examples of uses include door-intrusion beams, chassis members, reinforcing and mounting brackets, steering and suspension parts, bumpers, and wheels.[2][6]

Optional

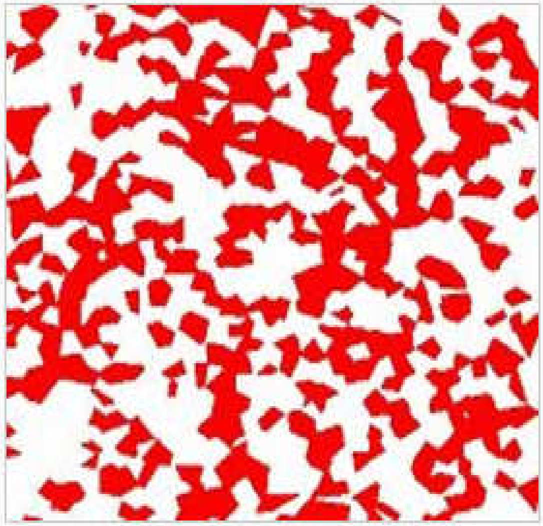
Dual-phase steel

WIKIPEDIA
The Free Encyclopedia

https://en.wikipedia.org/wiki/Dual-phase_steel

From Wikipedia, the free encyclopedia

Dual-phase steel (**DPS**) is a high-strength steel that has a ferrite and martensitic microstructure. DPS starts as a low or medium carbon steel and is quenched from a temperature above A_1 but below A_3 on a continuous cooling transformation diagram. This results in a microstructure consisting of a soft ferrite matrix containing islands of martensite as the secondary phase (martensite increases the tensile strength). Therefore, the overall behavior of DPS is governed by the volume fraction, morpology (size, aspect ratio, interconnectivity, etc.), the grain size and the carbon content.[1] For achieving these microstructures, DPS typically contain 0.06–0.15 wt.% C and 1.5-3% Mn (the former strengthens the martensite, and the latter causes solid solution strengthening in ferrite, while both stabilize the austenite), Cr & Mo (to retard pearlite or bainite formation), Si (to promote ferrite transformation), V and Nb (for precipitation strengthening and microstructure refinement).[2] The desire to produce high strength steels with formability greater than microalloyed steel led the development of DPS in the 1970s.[3][4]



Virtually generated microstructure of dual-phase steel.[1]

DPS have high ultimate tensile strength (UTS, enabled by the martensite) combined with low initial yielding stress (provided by the ferrite phase), high early-stage strain hardening and macroscopically homogeneous plastic flow (enabled through the absence of Lüders effects). These features render DPS ideal materials for automotive-related sheet forming operations.

Optional

Microalloyed steel

WIKIPEDIA
The Free Encyclopedia

From Wikipedia, the free encyclopedia

Microalloyed steel is a type of alloy steel that contains small amounts of alloying elements (0.05 to 0.15%), including niobium, vanadium, titanium, molybdenum, zirconium, boron, and rare-earth metals. They are used to refine the grain microstructure or facilitate precipitation hardening.[1]

These steels lie, in terms of performance and cost, between carbon steel and low alloy steel. Yield strength is between 500 and 750 MPa (73,000 and 109,000 psi) without heat treatment. Weldability is good, and can even be improved by reducing carbon content while maintaining strength. Fatigue life and wear resistance are superior to similar heat-treated steels. The disadvantages are that ductility and toughness are not as good as quenched and tempered (Q&T) steels. They must also be heated hot enough for all of the alloys to be in solution; after forming, the material must be quickly cooled to 540 to 600 °C (1,004 to 1,112 °F).[2]

Cold-worked microalloyed steels do not require as much cold working to achieve the same strength as other carbon steel; this also leads to greater ductility. Hot-worked microalloyed steels can be used from the air-cooled state. If controlled cooling is used, the material can produce mechanical properties similar to Q&T steels. Machinability is better than Q&T steels because of their more uniform hardness and their ferrite-pearlite microstructure.[3]

Because microalloyed steels are not quenched and tempered, they are not susceptible to quench cracking, nor do they need to be straightened or stress relieved. However, because of this, they are through-hardened and do not have a softer and tougher core like quench and tempered steels.[3]

Optional

300M ALLOY STEEL (4340M)

300M is a vacuum melted low alloy steel with the inclusion of vanadium and a higher silicon composition. It has a very good fatigue strength and resilience. Where fracture toughness and impact strength are crucial, 300M is a great choice.

www.twmetals.com/300m-bar-rod-wire.html

Applications:

- Aircraft Landing Gear
- Airframe Parts
- Missile Components
- Motorsport Applications

Typical Chemical Properties		
Minimum Properties	Tensile Strength , psi	280,000
	Yield Strength, psi	230,000
	Elongation	7%
	Rockwell Hardness	B 311 Max
Chemistry	Carbon(C)	.38 -.42%
	Chrome (Cr)	0.70-0.95%
	Manganese (Mn)	0.60-.90%
	Molybdenum (Mo)	0.30 - .50%
	Nickel (Ni)	1.65-2.0%
	Phosphorus (P)	P & S - 0.10 %
	Sulphur (S)	P & S - 0.10 %
	Silicon (Si)	1.45 - 1.80%
	Vanadium(V)	0.05 - 0.10 %
	Copper (Cu)	0.35%

Stiffness

انتخاب مواد با معیار سفتی

Stiffness

Stiffness is the ability of a material to maintain its shape when acted upon by a load. The concept of stiffness in metals is usually approached through Hooke's Law, which is concerned with the relationship between stress and strain (although Hooke's actual terms were load and extension). When a metal is loaded, the stress–strain curve is at first approximately linear and its slope is a measure of the stiffness of the metal. If the loading is in tension or compression the value of the slope is known as Young's modulus, or the modulus of elasticity, denoted by E in the engineering literature; when the loading is in shear it is known as the modulus of rigidity, or shear modulus, denoted by G. These two elastic constants are related through Poisson's ratio, v, as follows:

$$G = \frac{E}{2(1 + v)} \qquad (8.1)$$

Of course, the stress–strain relationship of materials in general is not always linear, and then stiffness must be measured by alternative parameters such as the tangent modulus or secant modulus. This also applies to metals as they start to enter the plastic range.

The importance of stiffness

There are three reasons why stiffness is important. One is concerned with stable deflections, another with absorption of energy and the third with failure by instability.

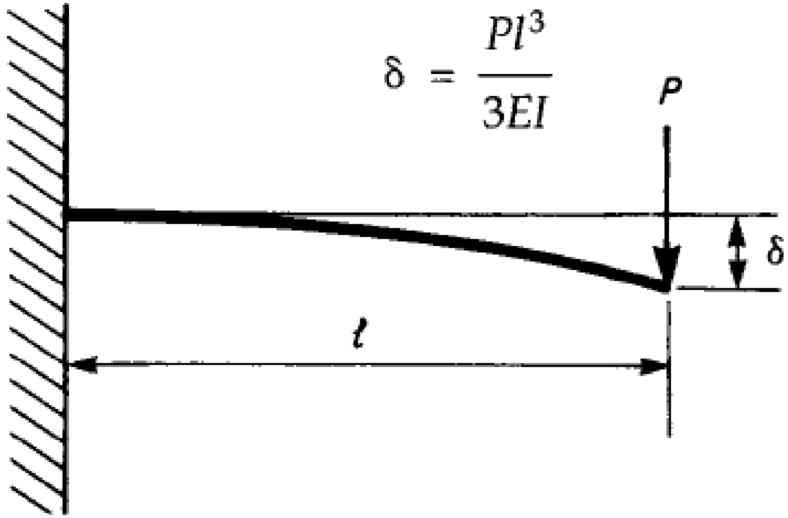


Figure 8.1 A cantilever subjected to an end load.

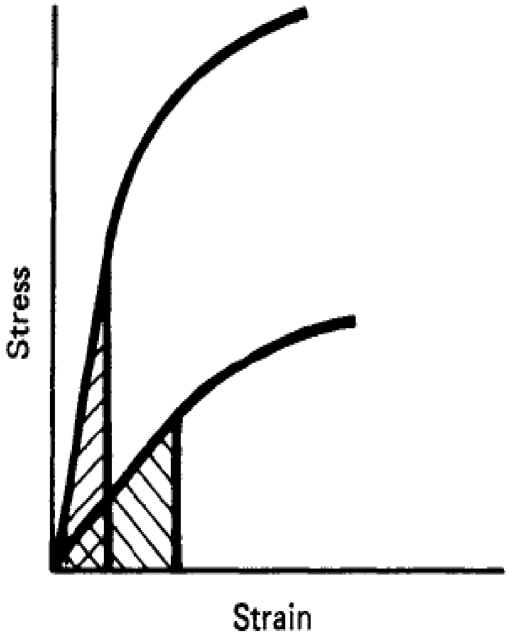


Figure 8.2 Stress–strain curves for two materials of differing stiffness.

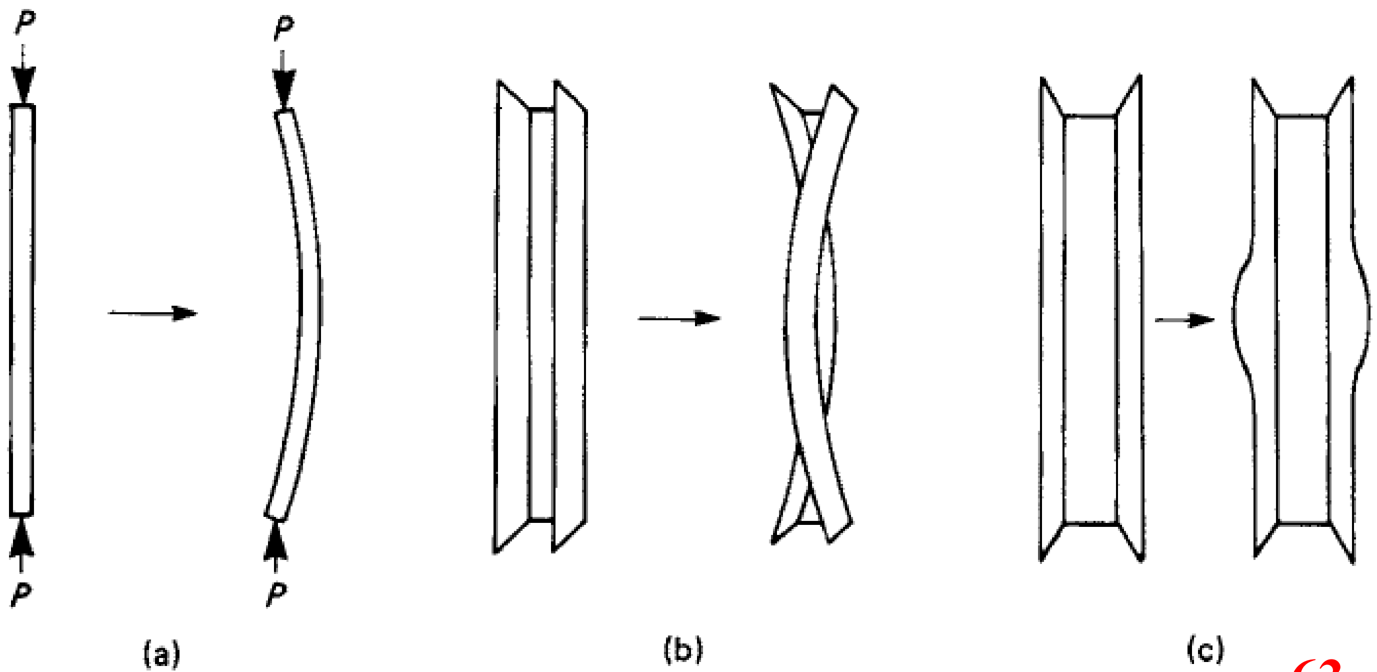
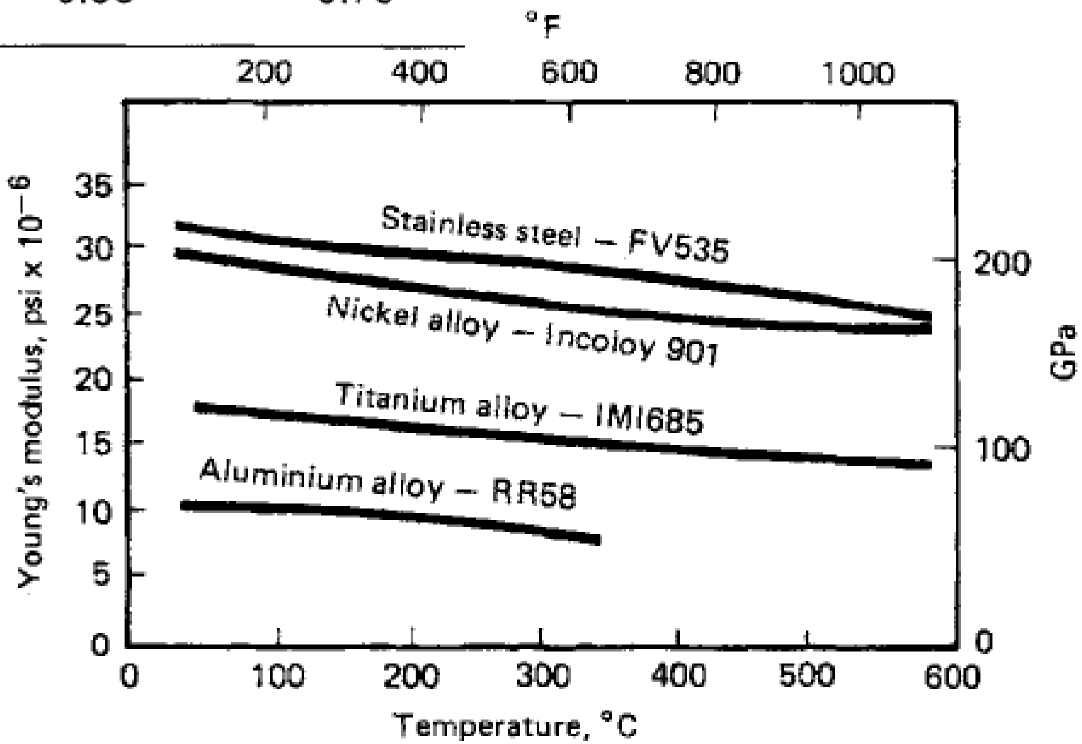


Figure 8.3 Some examples of failure by elastic instability.

Material	E (GPa)
Aluminum	70
Copper	124
Brass	110-120
Steel, Cast iron	200-210
Titanium	115

	Stiffness (GPa) E	*Density* (tonnes/m^3) ρ
Concrete (in compression)	27.0	2.40
Oak: parallel to grain	9.5	0.60
HM Carbon fibres	400.0	1.95
Aluminium N8 alloy	70.0	2.70
Steel	207.0	7.80
Glass fibre-reinforced concrete	25.0	2.40
Glass fibre: 70% resin reinforced plastic mat	10.0	1.50
Glass fibre: 50% resin reinforced plastic cloth	14.0	1.70
Glass fibre 20% resin reinforced plastic undirectional	48.0	2.00
Nylon 33% g.f.	3.5	1.20
Titanium	116.0	4.50
Unidirectional graphite-epoxy	137.0	1.50
45° cross-ply graphite-epoxy	15.0	1.50
Polypropylene	0.36	0.90



Fatigue

انتخاب مواد با معیار خستگی

Fatigue

- خستگی: نوعی تخریب تحت بارهای سیکلی یا نوسانی
- دو مشخصه اصلی:
  - عموما در تنشی بمراتب کمتر از استحکام ایستا
  - شکست ناگهانی و بدون اخطار قبلی
- اولین مورد ثبت شده: محور واگن قطار قرن ۱۹
- فرایند انتخاب مواد برای کاربرد خستگی به اندازه انتخاب برای استحکام ایستا و تافنس، موثر نیست.

Fatigue is a dangerous form of fracture which occurs in materials when they are subjected to cyclic or otherwise fluctuating loads. It occurs by the development and progressive growth of a crack and the two characteristic and equally unfortunate features of fatigue fracture are, first, that it can occur at loads much lower than those required to produce failure by static loading, and second, that during the more or less lengthy period of time that is required for fracture to propagate to the point of final failure there may be no obvious external indication that fracture is occurring.

Although fatigue failure is most familiar when it occurs in metals, probably no material is immune to this form of failure and other materials in which it is known to occur include concrete and polymers, and even living matter.

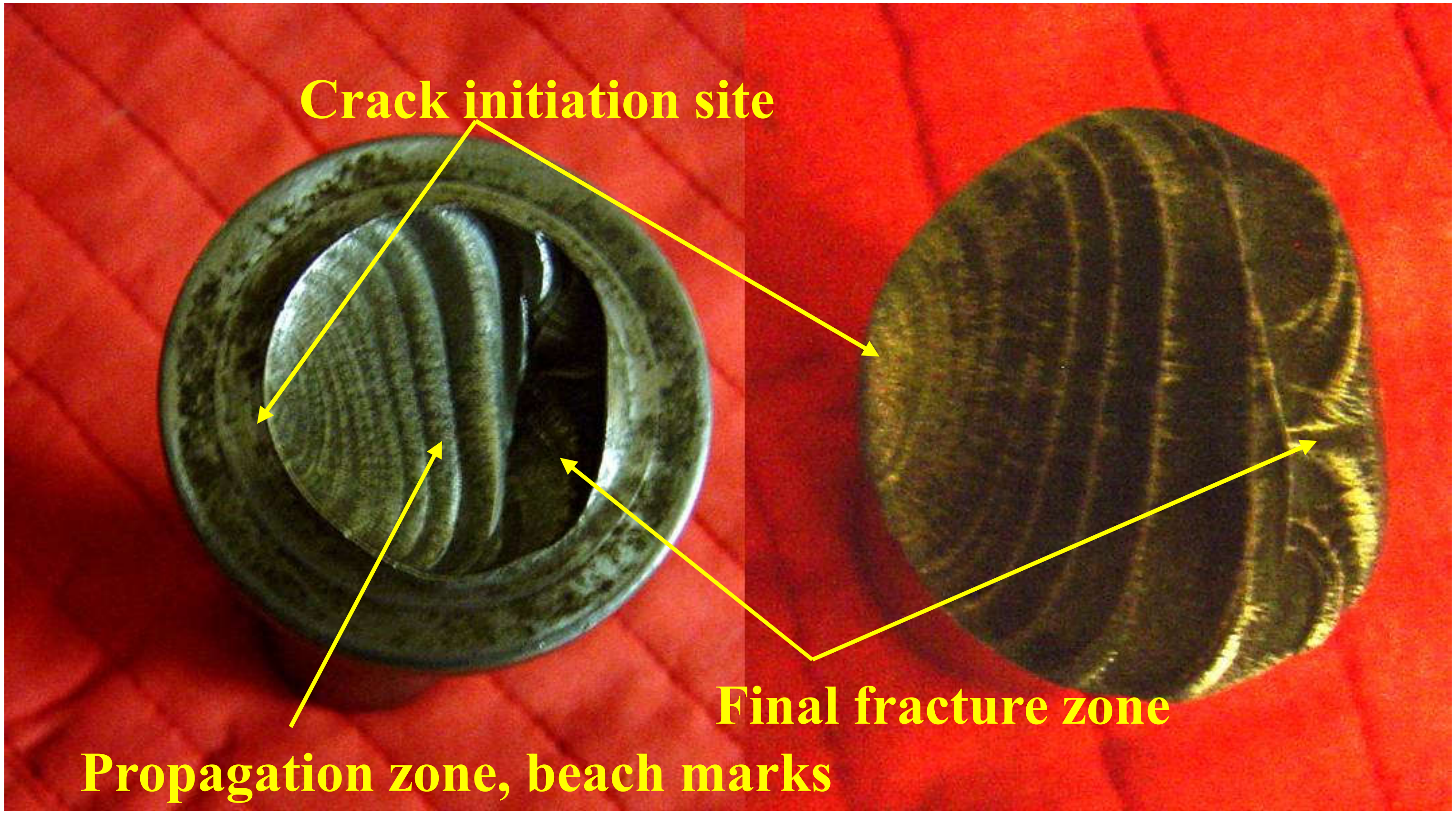
Fatigue Failure

- It has been recognized that a metal subjected to a repetitive or fluctuating stress will fail at a stress much lower than that required to cause failure on a single application of load.

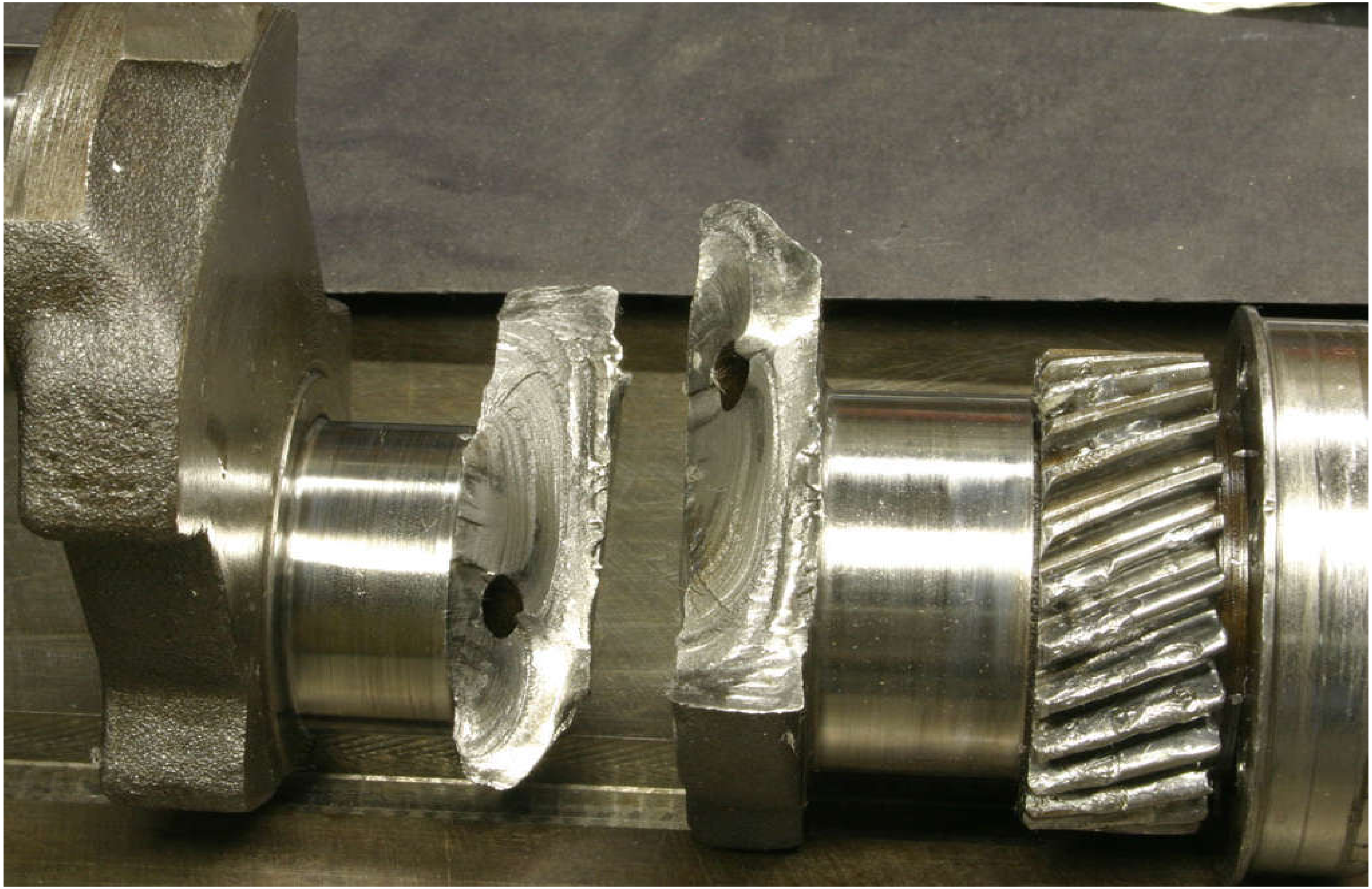
Fatigue failure is characterized by three stages:

- Crack Initiation (nucleation)
- Crack Propagation (growth)
- Final Fracture

Jack hammer component, shows no yielding before fracture.



Crank shaft



Ken Youssefi

Hawaii, Aloha Flight 243, 1988, a Boeing 737, an upper part of the plane's cabin area rips off in mid-flight. Metal fatigue was the cause of the failure.

Injuries (non-fatal): 65

Fatalities: 1

Investigation by the United States National Transportation Safety Board (NTSB) concluded that the accident was caused by **metal fatigue** exacerbated by crevice corrosion. The plane was 19 years old and operated in a coastal environment, with exposure to salt and humidity

Crack growth in smooth, hard specimens

In an unnotched low-strength material the fatigue strength will increase with matrix strength irrespective of whether the strengthening is achieved by cold working, alloying or heat treatment. However, as the matrix becomes progressively harder and Stage I nucleation becomes correspondingly more difficult, the stage is eventually reached when some additional factor must operate to bring about nucleation. This is available at the stress concentrations produced by second-phase particles. Thus, the methods used to improve the fatigue resistance of a high-strength material must be different from those applicable to a low-strength material because in the former case the cyclic stress required to initiate a crack will depend not on the hardness of the matrix but on the size, shape and distribution of non-metallic inclusions and other second-phase particles. To improve the fatigue performance of a high-strength material it is necessary to make it cleaner. This may necessitate the use of expensive processes such as electroslag refining for steels or the use of higher-purity base material for aluminium alloys.

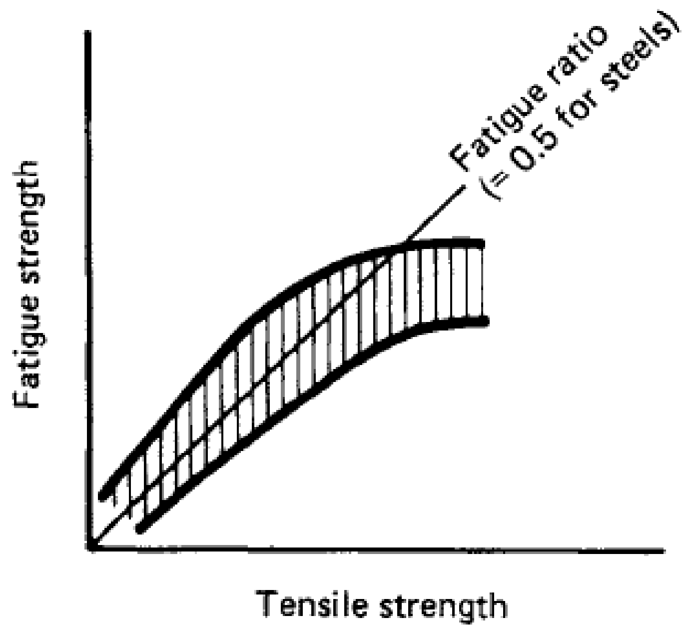


Figure 9.1 Relationship between fatigue strength and tensile strength.

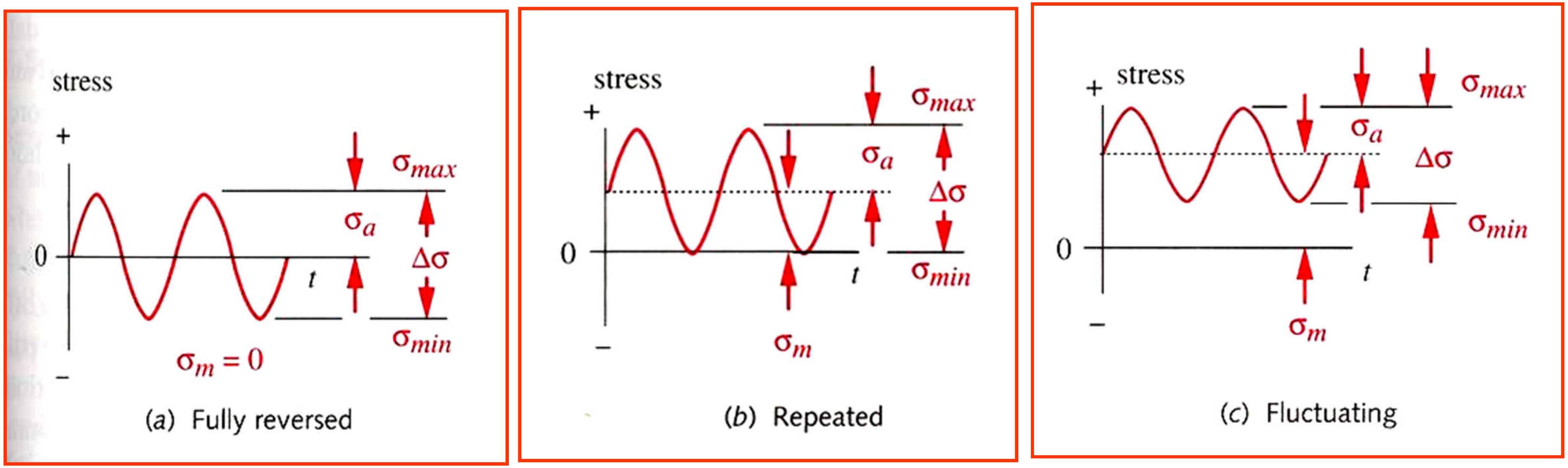
$$* \text{ Fatigue ratio, FR} = \frac{\text{Fatigue strength}}{\text{Tensile strength}}$$

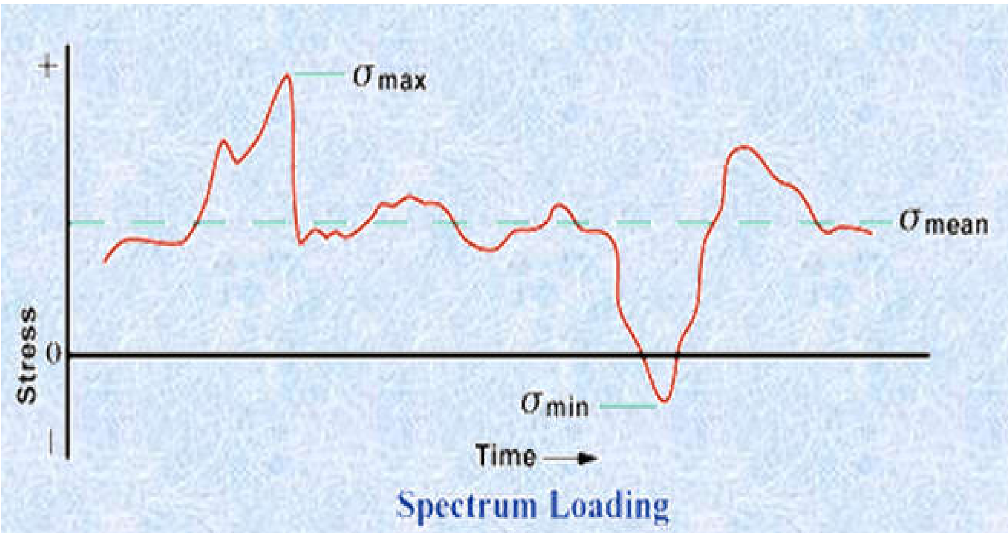
Crack growth in notched specimens

Whereas in unnotched specimens Stage I crack growth may occupy 90% or more of the total fatigue life, with Stage II growth taking up the remaining 10%, in specimens containing stress concentrations these figures can easily be reversed, with Stage II growth accounting for

more than 90% of the total life. Since Stage II growth is much faster than Stage I growth this means, unfortunately, that the total life is greatly reduced. Thus, a high stress concentration in a machine part can cause quite disastrous effects on fatigue performance. Therefore, wherever there are unavoidable features such as fillets, changes in cross-section and engineering details such as oil-holes, keyways and especially joints, strenuous efforts must be made to minimize the inevitable stress concentrations.

Fatigue Failure – Some Type of Fluctuating Stresses





Stress amplitude

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

Mean stress

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min}$$ stress range

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}$$ stress ratio

The assessment of fatigue resistance

There are two distinct lines of approach. One way is to use stress-life relationships, generally known as *S–N* curves, in which *S* is the applied stress and *N* is the total fatigue life measured in cycles of stress. The other way is to use fracture mechanics data to estimate rates of fatigue crack propagation (FCP).

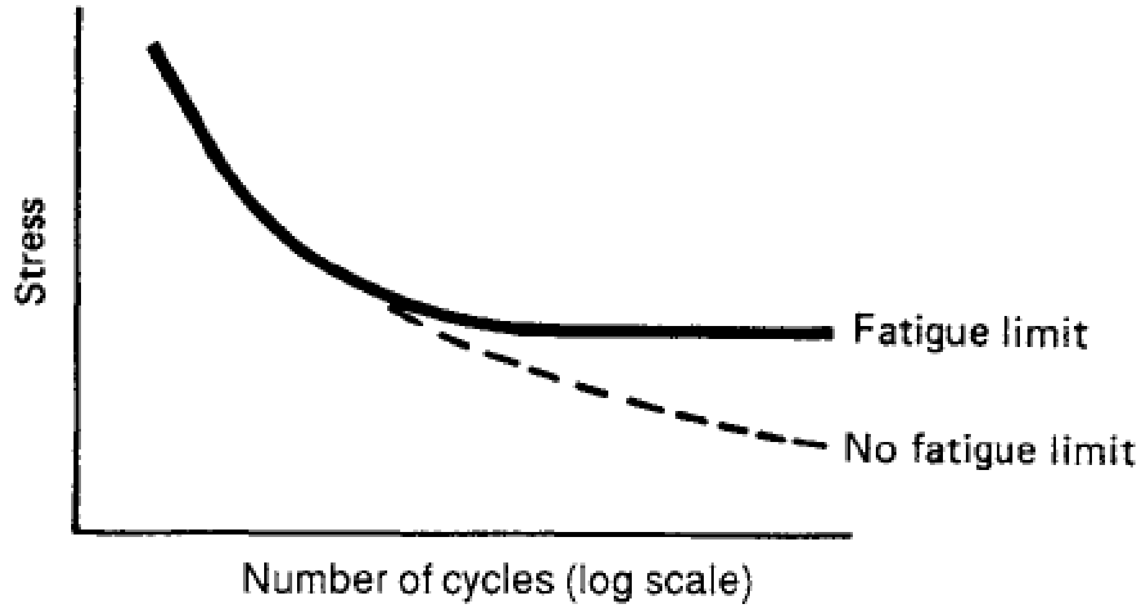
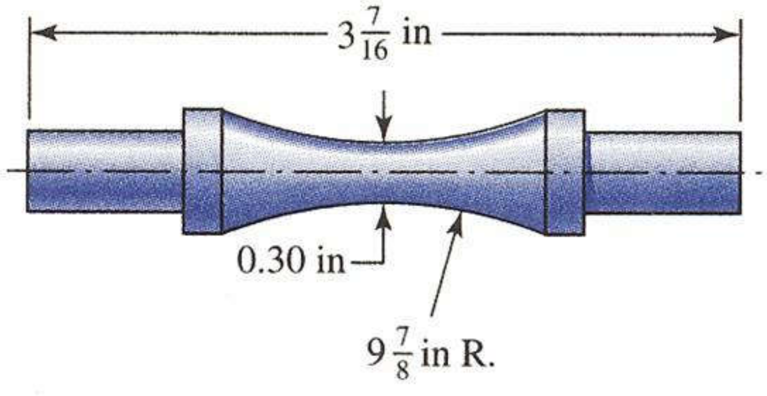
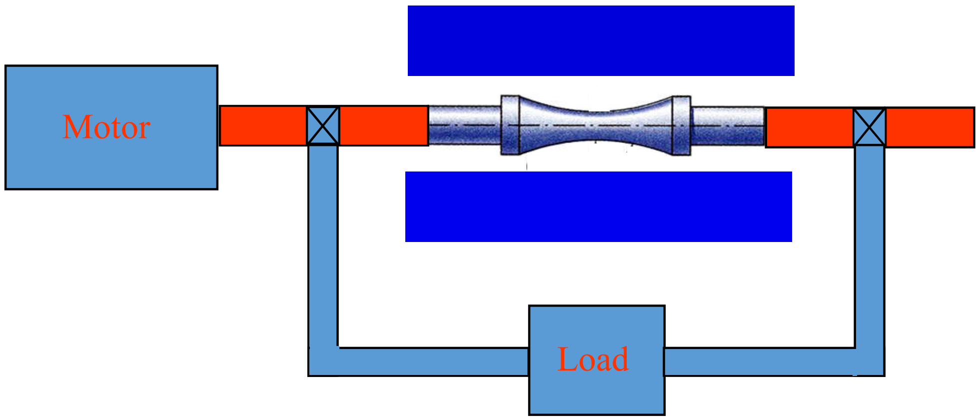


Figure 9.2 Typical stress-life (*S–N*) curves.



Test specimen geometry for R.R. Moore rotating beam machine. The surface is polished in the axial direction. A constant bending load is applied.

Typical testing apparatus, pure bending



Ken Youssefi; MAE dept., SJSU

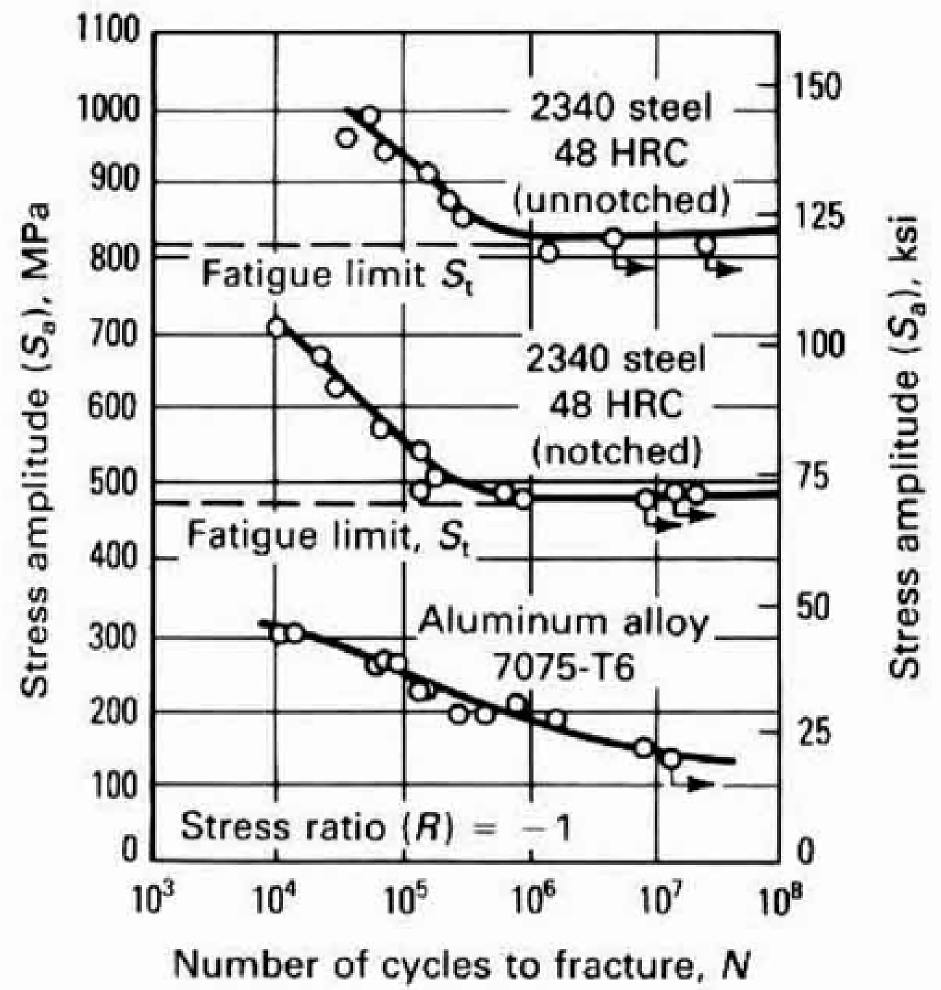
Rotating beam machine – applies fully reverse bending stress

- **تعداد نمونه های تست خستگی باید زیاد باشد تا تاثیر پراکندگی ذاتی نتایج به حداقل برسد (این آزمون به عواملی مانند کیفیت سطحی نمونه بسیار حساس است).**

S-N Curves

- The results of fatigue-crack initiation tests are usually plotted as maximum stress, minimum stress, or stress amplitude (S) **to** number of cycles to failure (N), using a **logarithmic** scale for the number of cycles.
- The number of cycles of stress that a metal can endure before failure increases with decreasing stress.
- For some engineering materials, such as steel and titanium, the S-N curve becomes horizontal at a certain limiting stress.
- Below this limiting stress, known as the *fatigue limit* ***or*** *endurance limit*, the material can endure an infinite number of cycles without failure.

Fig. 2 Typical *S-N* curves for constant amplitude and sinusoidal loading



- امروزه برای کاربردهای معمول و روزمره عمر کاری نسبتاً نامحدود قطعات، برای شرکت های تجاری چندان مطلوب نیست مانند قطعات خودرو (مزیت فروش لوازم یدکی)

- برای موادی که fatigue limit ندارند، fatigue life آنها را معمولا برای $۱۰^۸$-$۱۰^۷$ سیکل طراحی می کنند.

- استحکام خستگی تابعی از **استحکام ایستا و تافنس** می باشد. در فولادها در شرایط مناسب، تا مرحله ای حد خستگی در حدود نصف UTS می باشد و در استحکام های بالا (معمولا بیشتر از ۱۴۰۰ مگاپاسکال)، تقریبا ثابت می شود.

- در حالت کلی هر چه تافنس بالاتر باشد، رشد ترک نیازمند صرف انرژی بیشتر بوده و دشوارتر صورت می گیرد (عمر بیشتر)

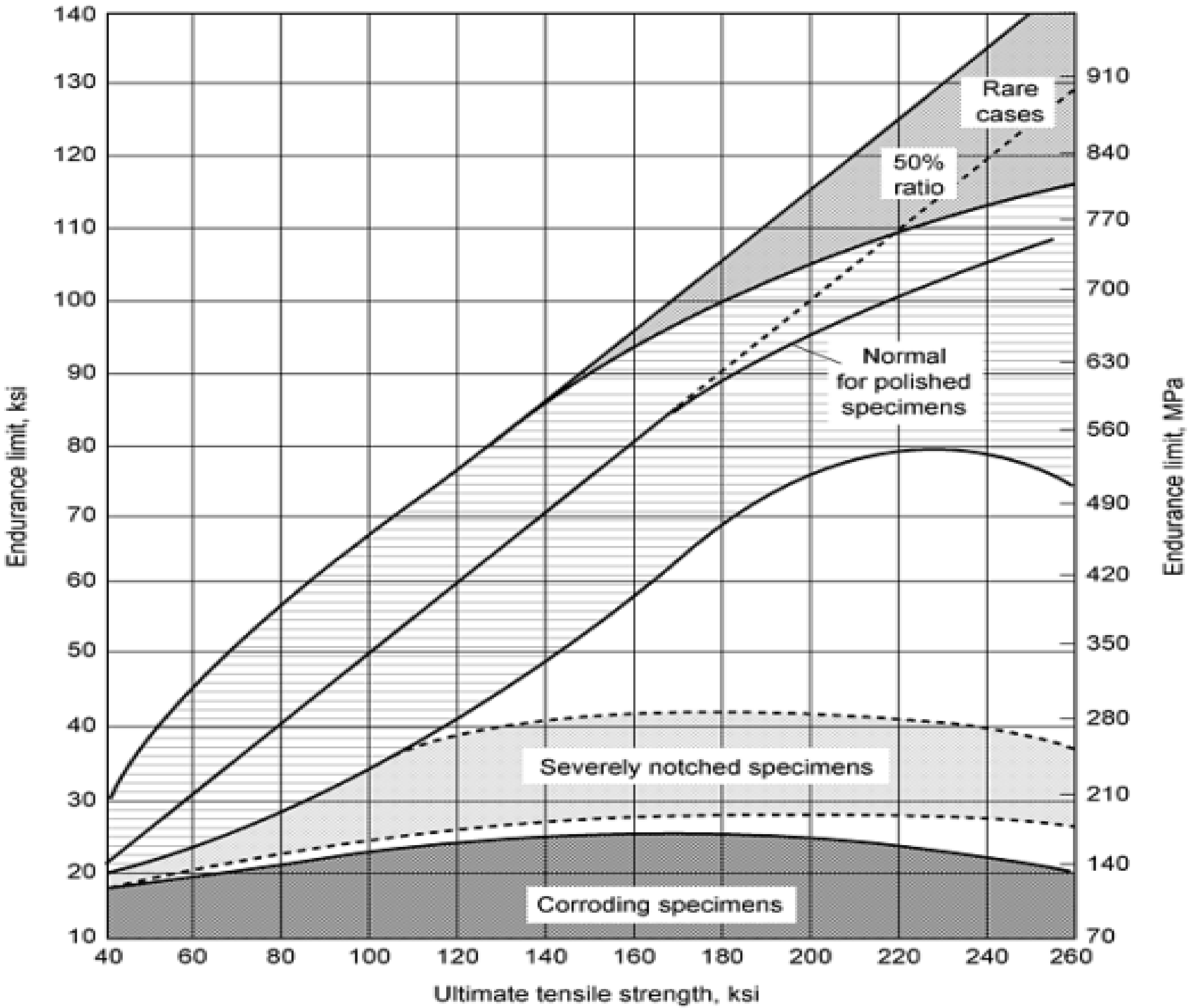


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Fig. 3 The relation between fatigue strength and tensile strength of polished, notched specimens and of specimens subjected to a corrosive environment. Source: Ref 7

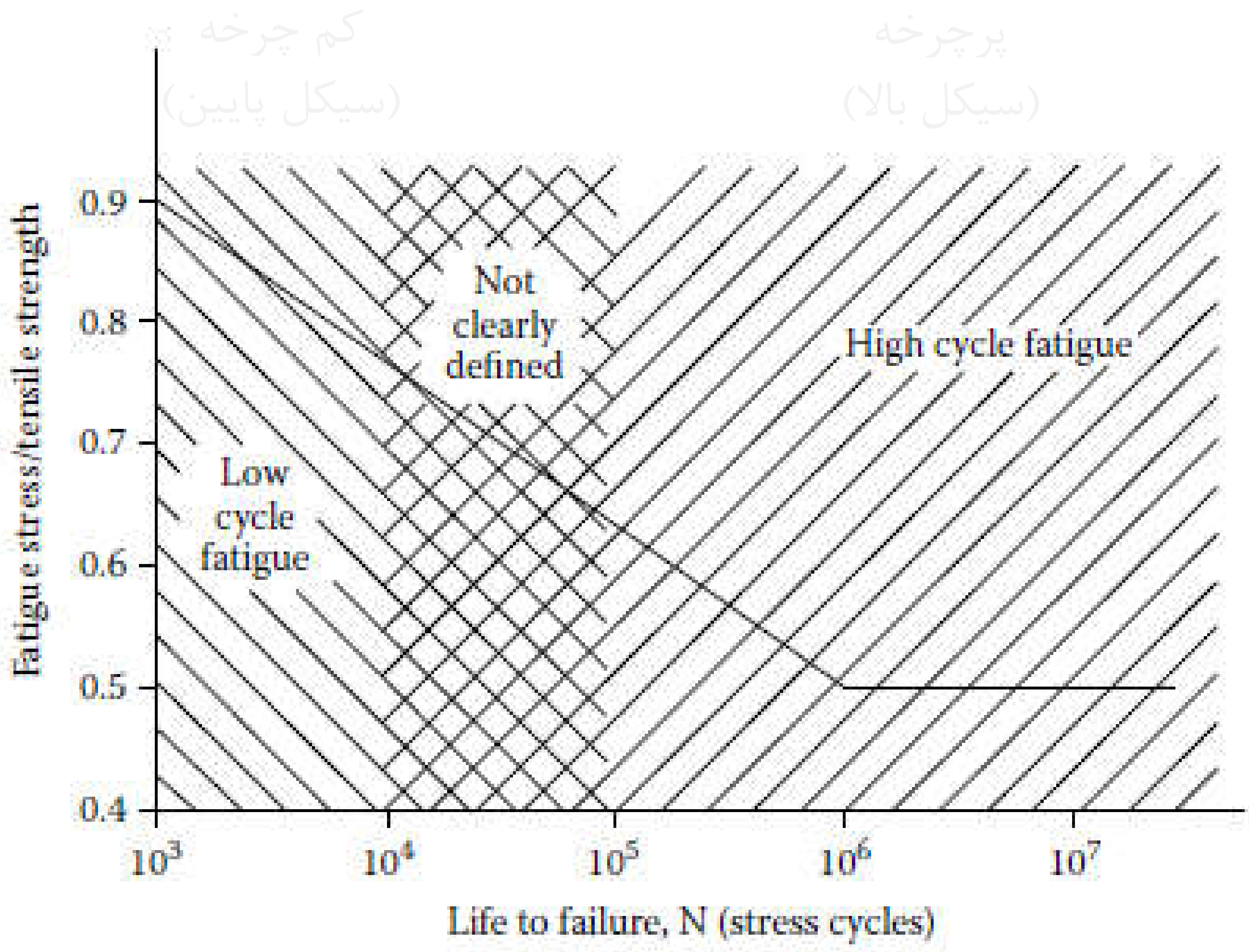
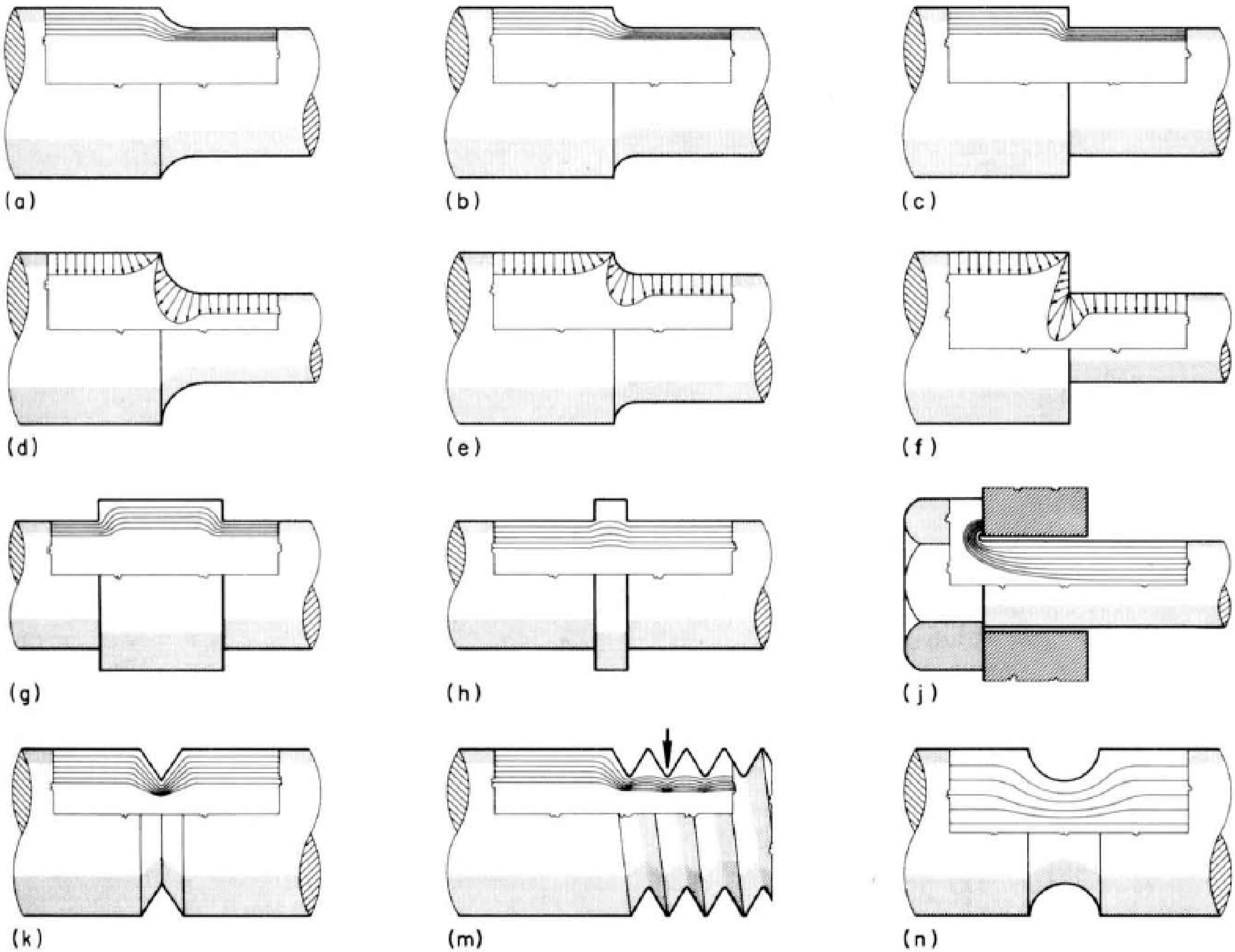


FIGURE 5.1 An S/N chart showing the ranges for low and high cycle fatigue failures. (VLCF would be off the left side of the chart.)

Fig. 21 Effect of stress raisers on stress concentration and distribution of stress at several changes of form in components

See text for discussion.



Fatigue-Crack Propagation

In large structural components, the existence of a crack does not necessarily imply imminent failure of the part. Significant structural life may remain in the cyclic growth of the crack to a size at which a critical failure occurs. The objective of fatigue-crack propagation testing is to determine the rates at which subcritical cracks grow under cyclic loadings before reaching a size that is critical for fracture. For an in-depth discussion, see the article "Fatigue Crack Propagation" in Volume 8 of the 9th Edition of *Metals Handbook*.

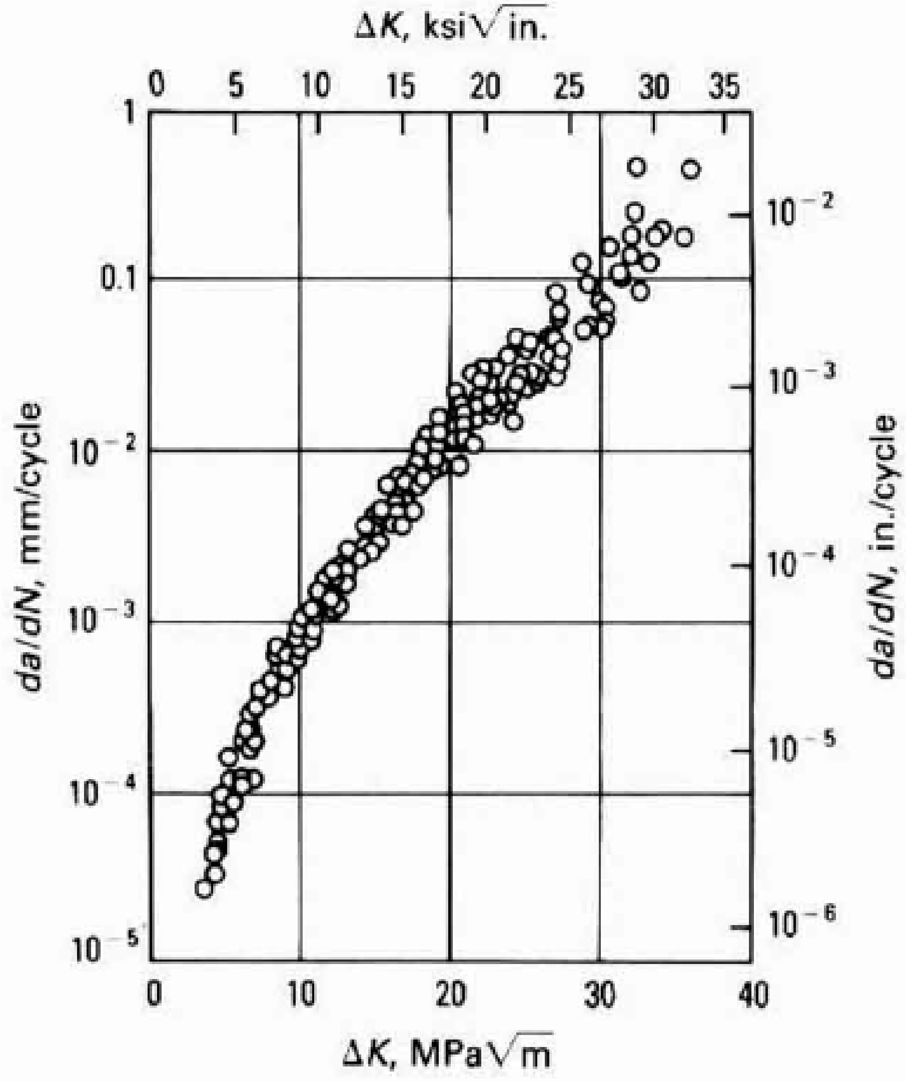
The growth or extension of a fatigue crack under cyclic loading is principally controlled by maximum load and stress ratio. However, as in crack initiation, a number of additional factors may exert a strong influence, including environment, frequency, temperature, grain direction, and other microstructural factors. Fatigue-crack propagation testing usually involves constant-load-amplitude cycling of notched specimens that have been precracked in fatigue.

Crack length is measured as a function of elapsed cycles, and these data are subjected to numerical analysis to establish the rate of crack growth, *da/dN*. Methods for numerically determining the crack-growth rate can be found in the article "Fatigue Data Analysis" in Volume 8 of the 9th Edition of *Metals Handbook*.

Crack-growth rates are expressed as a function of the crack-tip stress-intensity factor range, ΔK. The stress-intensity factor is calculated from expressions based on linear elastic stress analysis and is a function of crack size, load range, and cracked specimen geometry. Detailed information on the expressions used to define stress intensity from stress field analysis is provided in the article "Fracture Mechanics" in Volume 8 of the 9th Edition of *Metals Handbook*. Fatigue-crack growth data are typically presented in a log-log plot of *da/dN* versus ΔK (Fig. 4).

Fig. 4 Fatigue-crack propagation rate data for aluminum alloy 7075-T6

$R < 0$



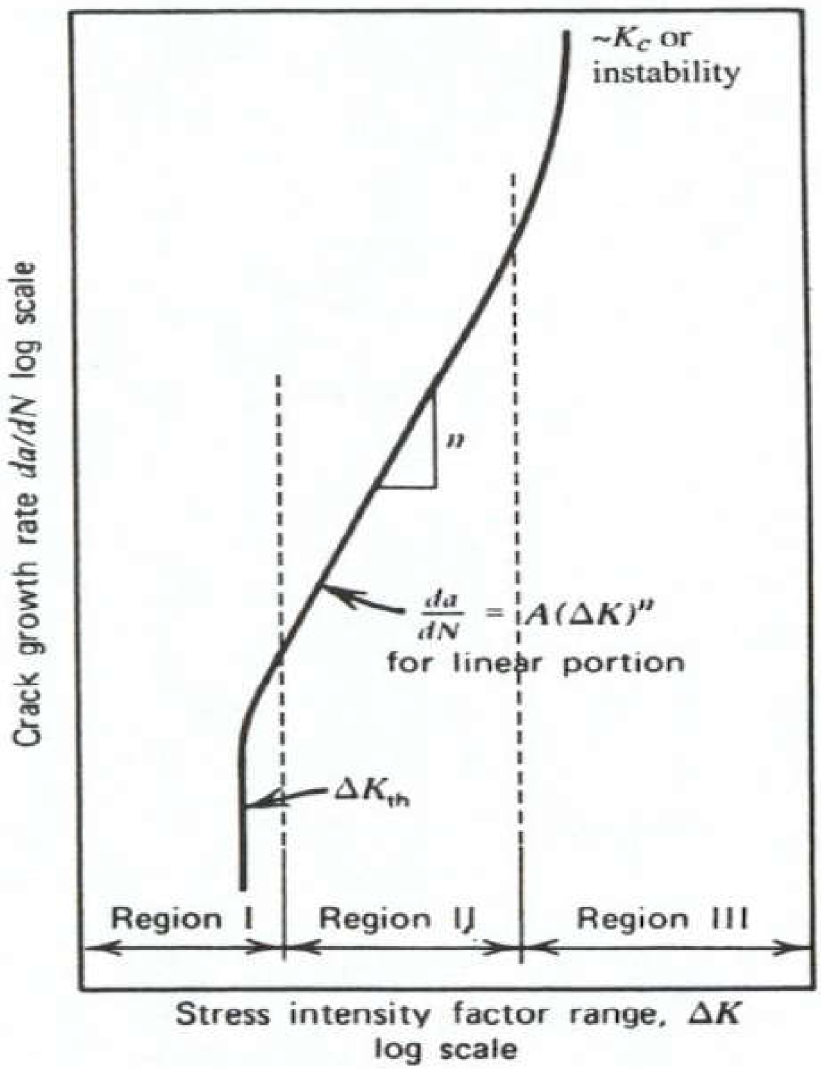
$$K = \alpha\,\sigma\sqrt{\pi c}$$

ضریب شدت تنش

FATIGUE CRACK GROWTH, da/dN-ΔK

- Log-log plot of *da/dN* versus ΔK has a sigmoidal shape that can be divided into **three regions**.

- **Region I** is the near threshold region and indicates a threshold value ΔK_{th}, below which there is no crack growth.
  - This threshold occurs at crack growth rates on the order of 1×10^{-10} m/cycle (~4×10^{-9} in./cycle) or less.
  - Microstructure, mean stress, and environment mainly control region I crack growth.

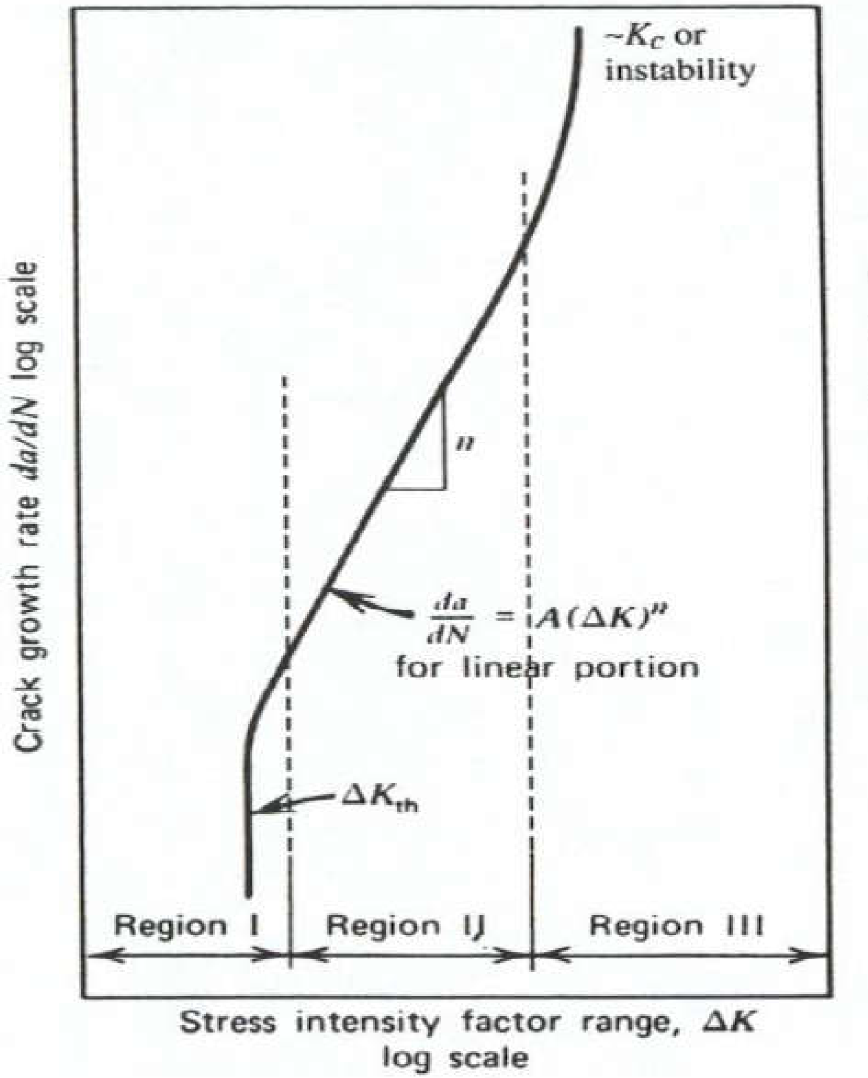


FATIGUE CRACK GROWTH, da/dN-ΔK

- **Region II** shows essentially a linear relationship between log *da/dN* and log ΔK, first suggested by **Paris**

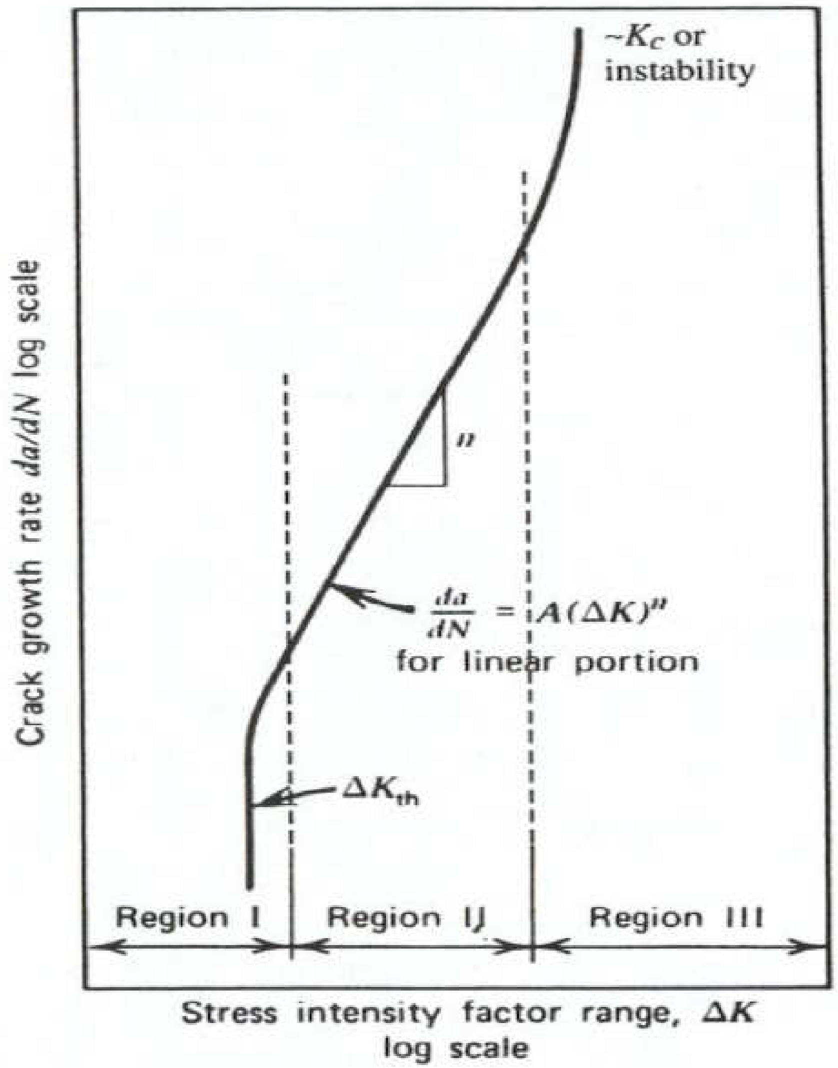
$$\frac{da}{dN} = A(\Delta K)^n$$

  - n is the slope of the curve
  - A is the coefficient found by extending the straight line to ΔK = 1 MPa√m (or 1 ksi√in.).
  - Region II (Paris region) corresponds to stable macroscopic crack growth. Microstructure and mean stress have less influence on fatigue crack growth behavior in region II than in region I.



FATIGUE CRACK GROWTH, da/dN-ΔK

- In **region III**
  - the fatigue crack growth rates are very high as they approach instability
  - little fatigue crack growth life is involved.
  - this region is controlled primarily by **fracture toughness K_c or K_{Ic}.**



FATIGUE CRACK GROWTH, da/dN-ΔK

- For a given material the fatigue crack growth behavior shown in Fig. 6.12 is essentially the same for different specimens or components.

- This allows fatigue crack growth rate versus ΔK data obtained under constant amplitude conditions with simple specimen configurations to be used in design situations.

$$\Delta S \text{ and } a \longrightarrow \Delta K \longrightarrow da/dN \longrightarrow N_f$$

- In many cases, integration of Paris by extrapolating to both regions I and III may be satisfactory as it often gives conservative fatigue crack growth life values.

برخی عوامل مؤثر بر حد خستگی و حد تحمل

❑ اثر نوع بارگذاری (K_p)

تنش حد خستگی و حد تحمل به نوع بارگذاری وابسته است. یعنی نتیجه بدست آمده از آزمایش خمش چرخان، کشش - فشار و .... با هم مساوی نیست. بدین منظور ضریب K_p=1 برای بارگذاری خمش چرخان در نظر گرفته شده است. و ضریب K_p برای بارگذاری های دیگر به شرح زیر تعریف شده است.

$$\sigma_D = K_p \cdot \sigma_{D0}$$

σ_{D0} در این رابطه حد خستگي تحت بار خمشی چرخان است.

خمش صفحه اي $K_p = 1.05$

کشش – فشار $K_p = 0.9$

پیچش $K_p = 0.6$

❑ اثر اندازه قطعه (Ke)

نتایج آزمایشات نشان می دهد که تحت شرایط مساوی هر چه ابعاد قطعه بزرگتر شود حد تحمل آن کمتر می شود. دلیل اثر اندازه قطعه روی حد خستگی از تفاوت گرادیان تنش، اندازه و تعداد عیوب داخلی ناشی می شود.

❑ اثر کیفیت سطح (Ks)

آزمايشات نشان مي دهد كه تحت شرايط كاملاً مساوي، حد خستگي به شدت به كيفيت سطح بستگي دارد و حد خستگي يك نمونه با زبري سطحي بسيار كم, از حد خستگي نمونه اي با زبري سطح زياد, بيشتر است.

❑ اثر تنشهای پسماند

تمامي تنش هاي پسماندي كه در جهت مخالف تنش اعمال شده بر قطعه اثر مي كنند **اثر مثبتي** روی عمر قطعه دارند، در حالتي كه اين تنش را بتوان اندازه گرفت بايد مقدار آن را با تنش متوسط (σ_m) بصورت جبري جمع شود (اگر در يك صفحه عمل كنند) و بصورت هندسي جمع شود اگر در صفحات مختلف اثر مي كنند.

❑ اثر تمرکز تنش kt

هنگامی که یک قطعه دارای ناپیوستگی هندسی باشد در آن تمرکز تنش بوجود می آید. جداول تمرکز تنش برای شکلهای مختلف ناپیوستگی در کتب مرجع وجود دارد. K_t نسبت تنش ماکزیمم واقعی اعمال شده را به تنش اسمی بیان می کند

$$K_t = \frac{\sigma_{max}}{\sigma_{nom}}$$

- در انتخاب مواد به دو طریق می توان عمر مواد تحت بار تناوبی را افزایش داد:
  1. جلوگیری از و یا به تاخیر انداختن مرحله جوانه زنی
  2. تاخیر مرحله رشد ترک

1. انتخاب مواد با معیار مرحله جوانه زنی:

از آنجایی که جوانه زنی عموما از سطح شروع می شود عملیات سطحی بسیار حائز اهمیت است:

- سختی نسبتا زیاد در سطح
- صاف بودن (smooth) و کیفیت مناسب سطح
- وجود تنش های پسماند فشاری در سطح

2. انتخاب مواد با معیار مرحله رشد ترک:

- استحکام و تافنس توامان بالا باشد.

❖ افزایش دما عموما باعث کاهش عمر خستگی می شود (کاهش استحکام، ...)

❖ خستگی و سایش از مهمترین عوامل خرابی های دینامیکی هستند.

❖ **مثال های قطعات تحت خستگی:** بال هواپیما، میل لنگ خودرو، روتور ها و شفت ها، ایمپلنت پا، دریچه مصنوعی قلب، پره های توربین، غلطک های نورد (خستگی حرارتی)، فنرهای خودرو، سیستم های حفاری معادن (corrosion fatigue)

Creep and Temperature Resistance

انتخاب مواد برای کاربردهای دمای بالا و خزشی

Creep and temperature resistance

Creep is deformation that occurs over a period of time. Under certain conditions it will, if allowed to do so, culminate in fracture. Generally, creep is the result of an externally applied load but can also occur as the result of self-weight. Lead sheet, when used on an inclined roof or vertical face, will, after a period of years, be thicker at the bottom than it is at the top; not necessarily a serious matter.

After extensive creep, however, the lead will often exhibit cracks, which is more serious. There are thus two aspects to the creep phenomenon, one being concerned with deformation; the other with fracture or creep rupture. A typical deformation-limited situation is that of a blade in a steam turbine which must not lengthen in service to the point at which it fouls the casing. [redacted]

- Creep, by definition, is time-dependent strain occurring, under stress.
- After a period of time, creep deformation may terminate in fracture by stress rupture (also called creep rupture).
- Time, Temperature, Stress

- خزش: تغییر شکل (کرنش) وابسته به زمان و معمولا در دمای بالا (بیشتر از $0.3T_m$ یا $0.5T_m$)
- تضعیف شدن ریز ساختار و افت خواص مکانیکی آلیاژ
- برای قطعاتی که در دمای بالا کار می کنند مانند پره های توربین و سایر قطعات نیروگاهی
- در بسیاری از موارد، سبب کشیده شدن پره ها و تغییرات ابعادی آنها
- خزش می تواند سبب ایجاد حفرات خزشی در ریزساختار شده که به هم پیوستن و اتصال آنها منجر به ایجاد ترک و اشاعه آن می گردد.

Fig. 44 Creep damage (bowing) resulting from overheating in a cobalt-base alloy turbine vane

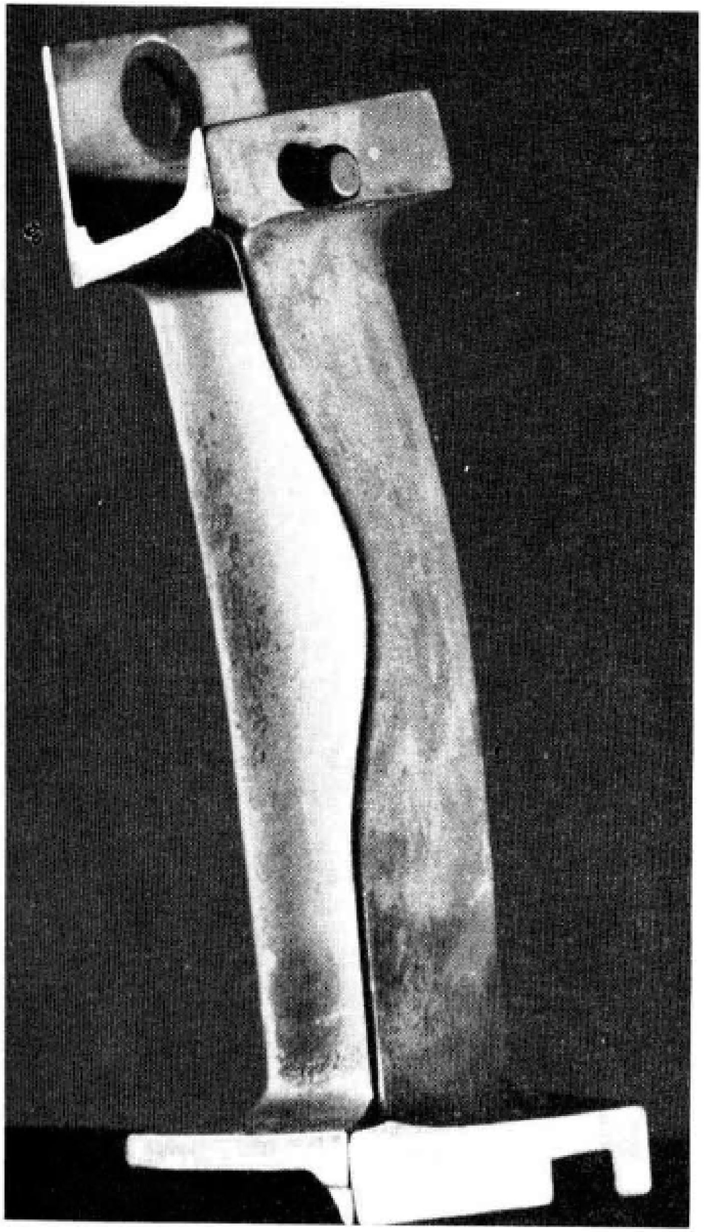
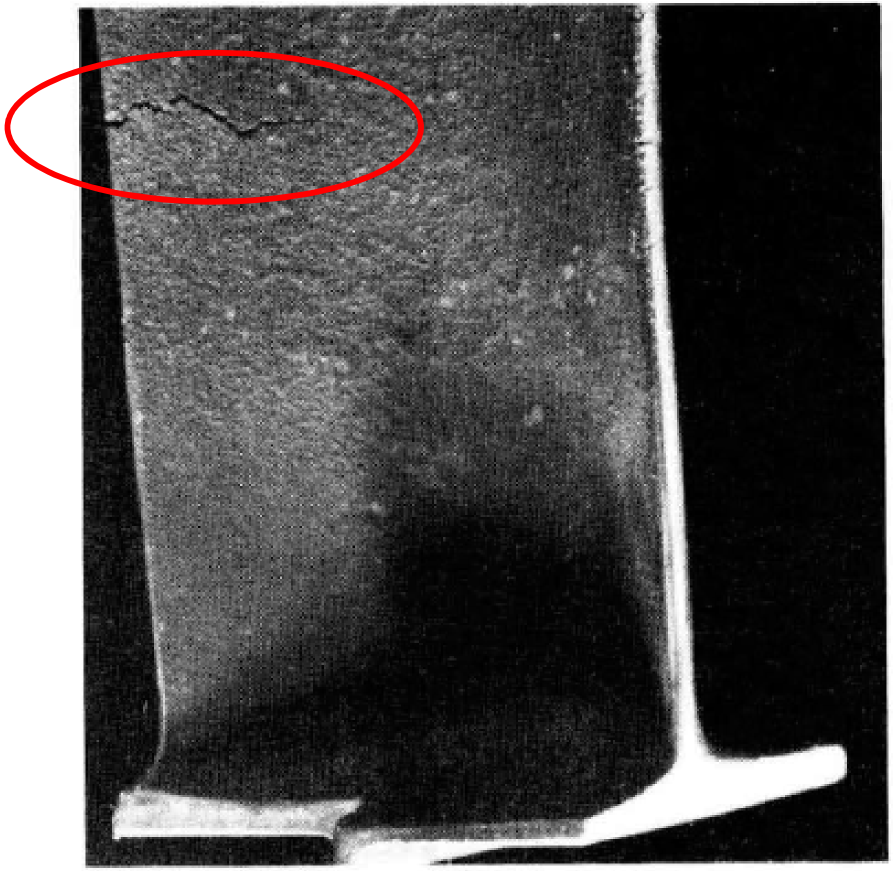


Fig. 47 Cracking due to creep in a cast nickel-base alloy turbine blade

1.5 ×



Creep Curve

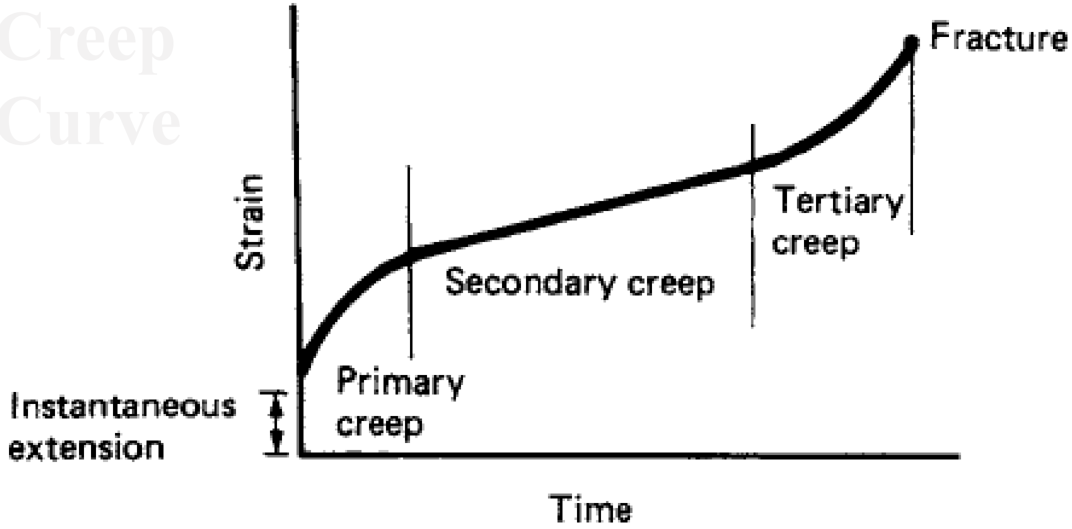


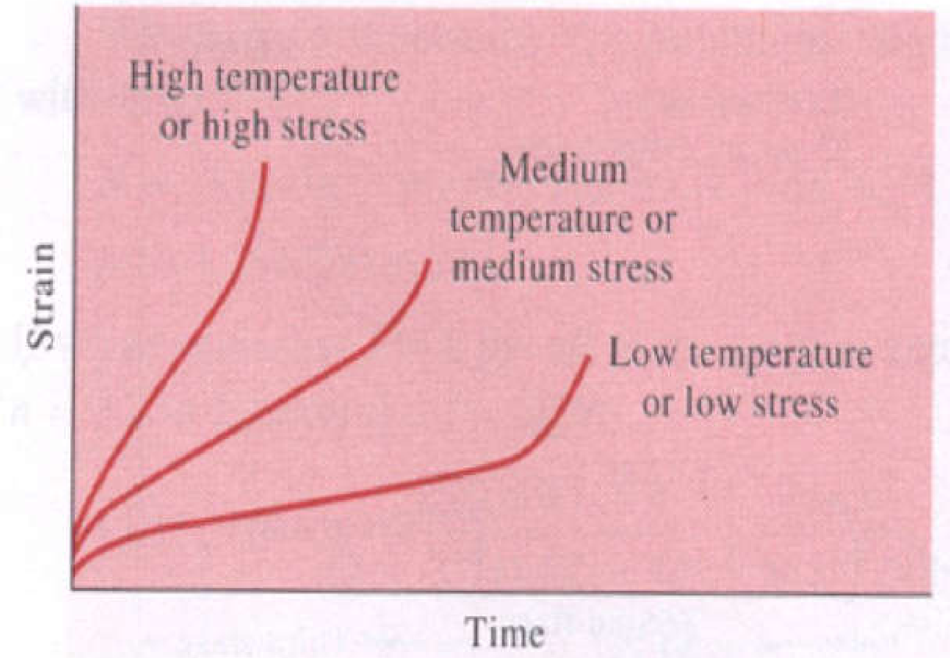
Figure 10.1 Conventional creep curve, showing the stages of creep.

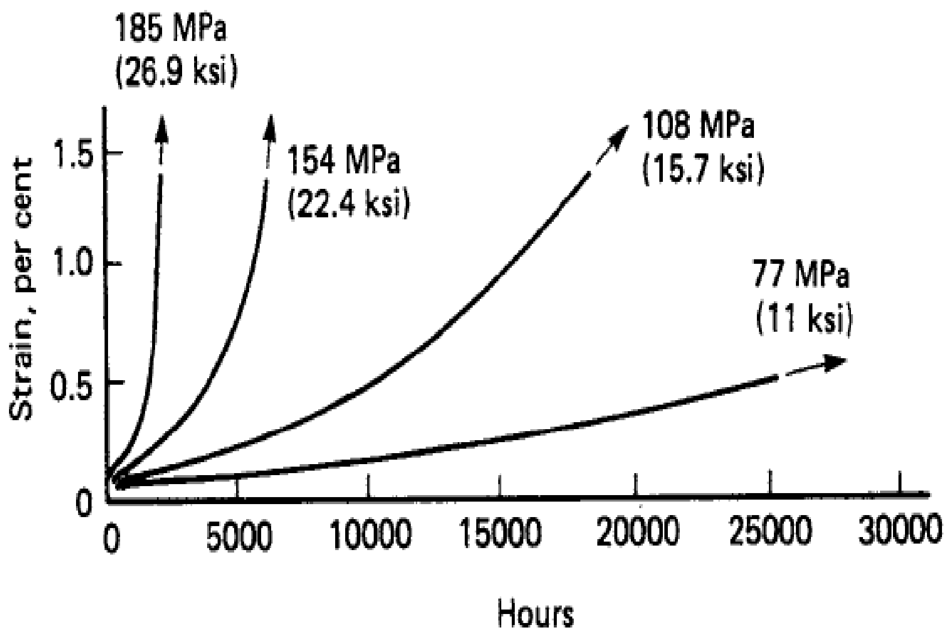
The strain rate during the steady-state regime is often described as follows:

$$\dot{\epsilon}_{ss} = A\sigma^n \exp\left(\frac{-Q}{RT}\right) \quad = \dot{\varepsilon}_{min}$$

where σ is stress, T is temperature (°K), A is a constant, n is the stress exponent, and Q is the activation energy for creep (J/mole). These are material constants which must be determined experimentally; n typically takes a value between 3 and 8, but may be higher.

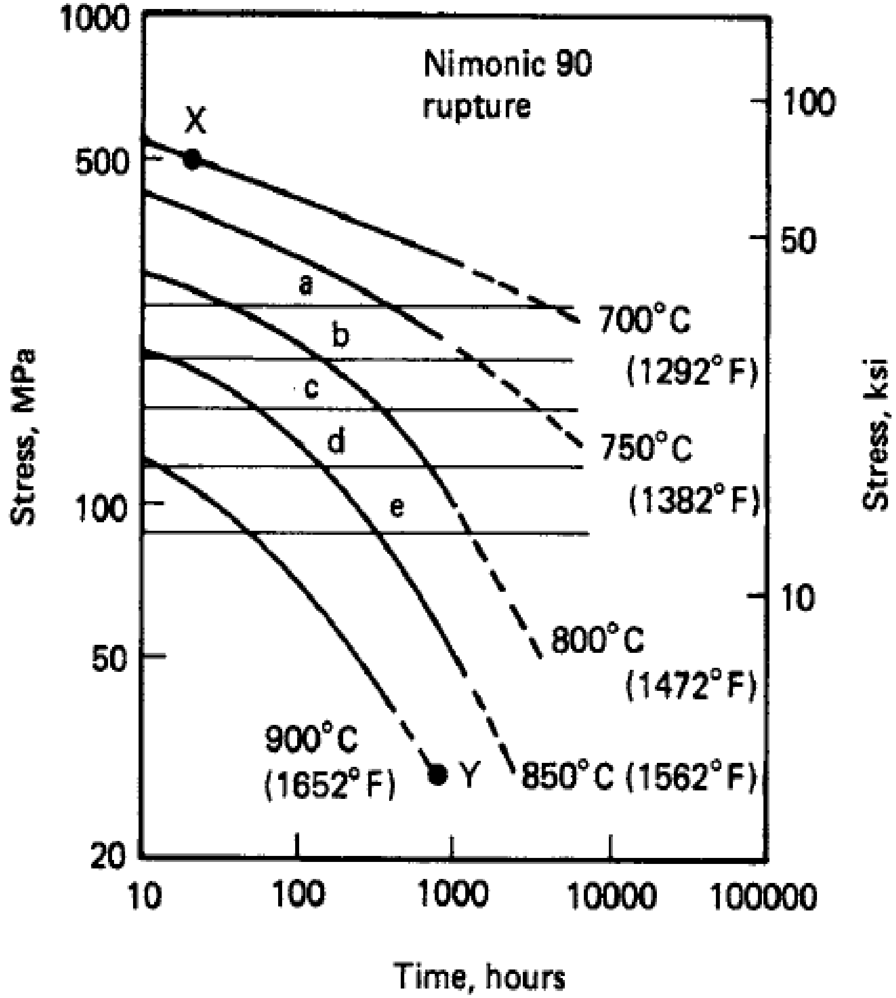
Effect of Temperature & Stress

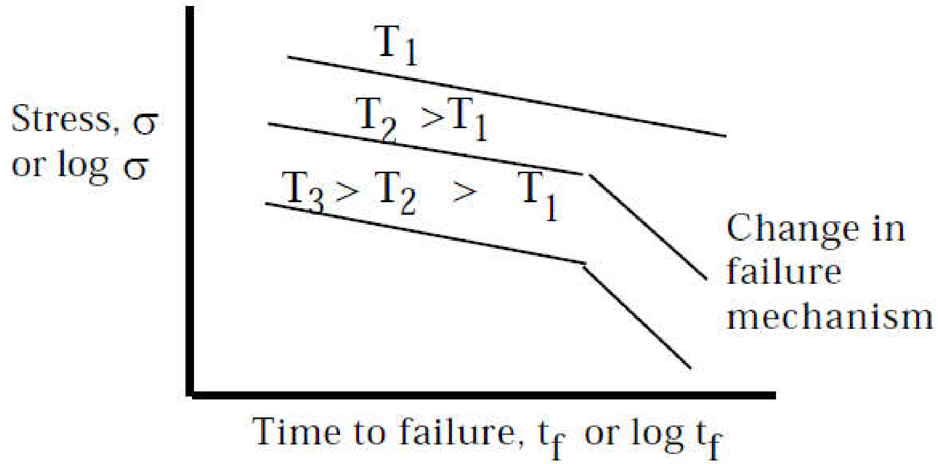




Stress Rupture Curve

For design purposes, however, it is not necessary to refer to the complete creep curve and there are various ways of providing the necessary information (Figure 10.3a,b). In general, there is more information available relating to creep rupture than to creep strain. Just as in short-term testing it is easier to determine tensile strength rather than a proof stress, so in creep testing it is much easier to test for rupture than for a given strain. The standard creep-rupture test is carried out at constant stress and temperature, and measures the time to rupture with no account being taken of deformation, except for total elongation of the fractured test piece to provide a criterion for rupture ductility. This information can be useful for quality control and the comparison of materials. For many design purposes, however, it is inadequate and the data for materials are often incomplete. This is the





Stress rupture plots for various temperatures

One of the oldest ideas is that creep rupture data are linear when the temperature of test is plotted against the logarithm of time to rupture.

Larson and Miller[2] on the other hand, taking as their starting point the Arrhenius relationship

$$\frac{d\epsilon}{dt} = A \exp\left(\frac{-Q}{RT}\right)$$

in which Q is the creep activation energy and R the universal gas constant, proposed that plots at constant stress of $1/T$ against $\log t_r$ would intersect at a single point having the coordinates 0, –C (Figure 10.5). Their correlation parameter is given by $\text{LMCP} = T(C + \log_{10} t_r)$.

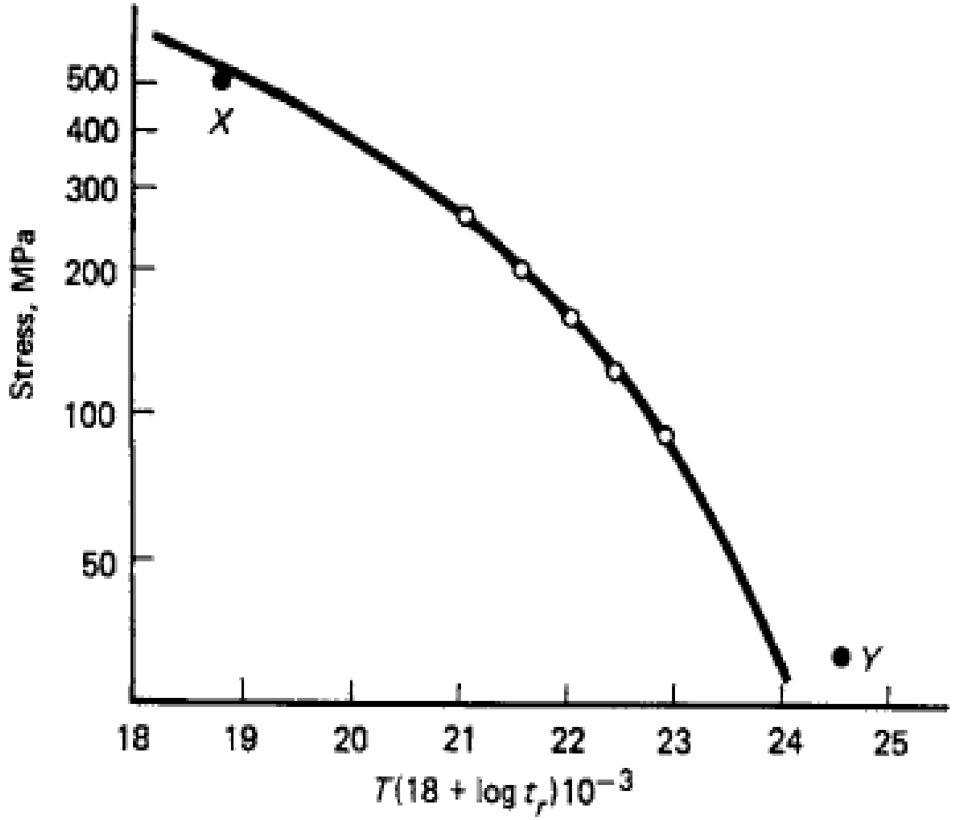


Figure 10.7 Correlation curve for creep rupture of Nimonic 90 using the Larson–Miller correlation parameter.

Originally, Larson and Miller proposed that the value of C in their parameter should be 20 for all materials (t is then in hours). However it is found that in practice C can vary from 17 to 23, but nevertheless the correlation parameter $T(20 + \log t)$ is commonly used as a basis for comparisons within collections of widely disparate materials (Figure 10.9). Such comparisons are useful, if of limited accuracy.

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$$T(\log t_r + C) = m.$$

Material	Larson–Miller C
Various steels and stainless steels	≈20
Pure aluminum and dilute alloys	–
S-590 alloy (Fe base)	17
A-286 stainless steel	20
Nimonic 81A (Ni base)	18
1% Cr–1% Mo–0.25%V steel	22

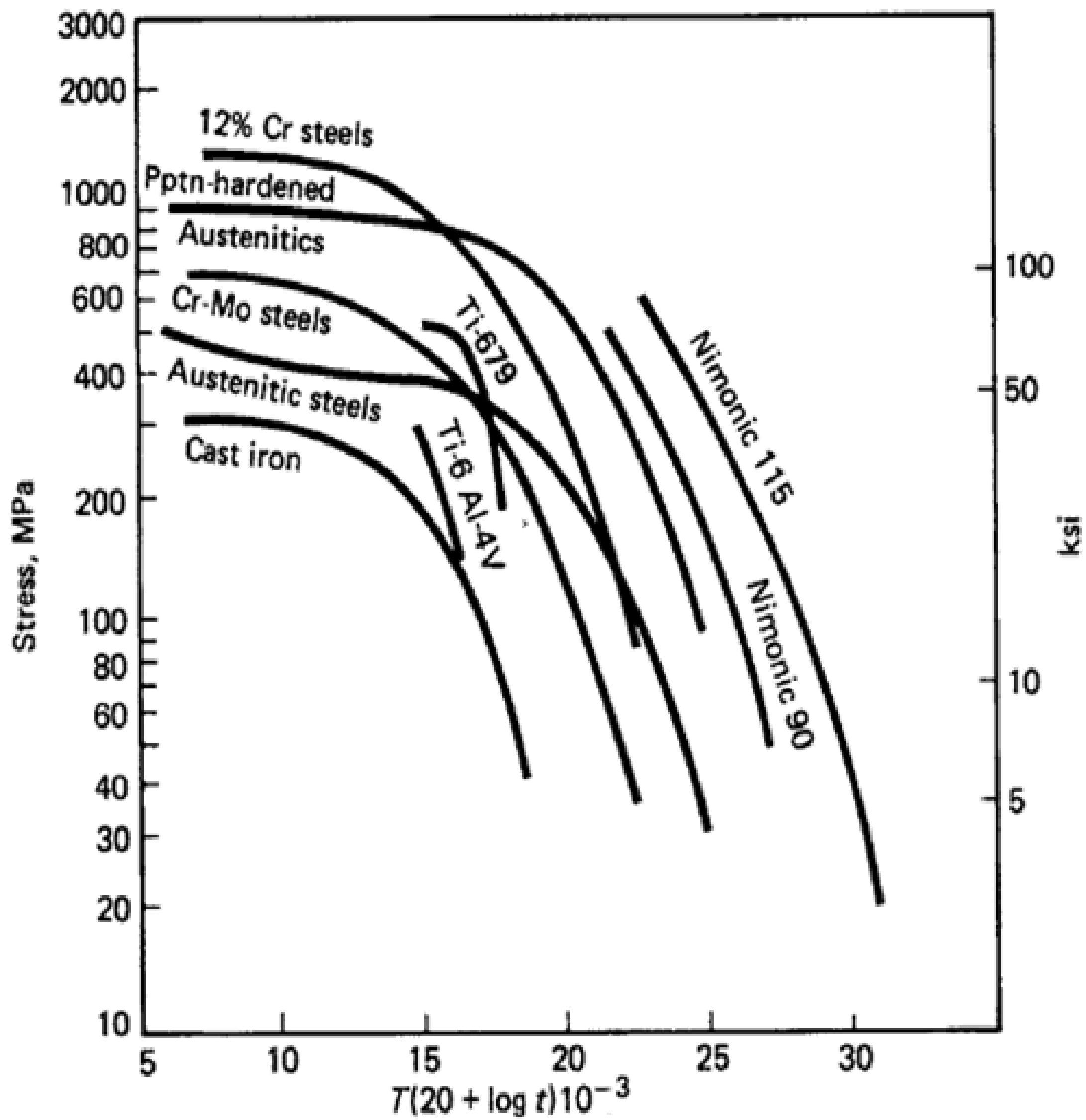

Figure 10.9 Creep resistance of various materials using the Larson-Miller correlation parameter. (Data by courtesy of Wiggin Alloys Ltd. (nickel

هدر خروجی سوپرهیتر دمای بالا

Alloy Steel SA 335

Standard	Grade	Chemical composition						
		C	Si	Mn	P	S	Cr	Mo
SA335	P12	0.05-0.15	0.50-1.0	0.30-0.60	≤0.030	≤0.030	1.00-1.50	0.50-1.00

مشخصات خزشی آلیاژ SA 335 P12 در دماهای مختلف

درجه حرارت $(^{\circ}C)$	$\sigma_{10000\,h}$ (MPa)	$\sigma_{100000\,h}$ (MPa)	$\sigma_{200000\,h}$ (MPa)	$\sigma_{1000000\,h}$ (MPa)
489	268	137	126.5	93
492	248	133.6	123	87

$$T(\log t_r + C) = m.$$

اثر تغییر شرایط بهره‌برداری - مثال هدر خروجی SH/HT

σ (psi)	LMP	T (°R)	t (h)		T (°C)
6500	37.2×10^3	1457	≈340000		536
6500	37.2×10^3	1467 (10°F ≈ 5°C)	≈228000	≈ 0/67 %	542
6500	37.2×10^3	1477 (20°F ≈ 10°C)	≈153500	≈ %45	547

در یک تنش ثابت (≈ 45 MPa) افزایش دما به مقدار ۶ درجه سانتیگراد، ۳۳٪ عمر قطعه را کاهش داده است.

The development of creep-resisting alloys

- Melting point
- Crystal (lattice) structure
- Solid solution strengthening
- Cold work
- Precipitation and dispersion-hardening

that the first requirement of a creep-resisting alloy is a high melting point. In agreement with this, experience shows that, in any alloy, it is difficult to produce useful mechanical properties at temperatures higher than 2/3 T_m for that material and sometimes the actual achievement is much less (see Table 10.1).

Creep and temperature resistance

TABLE 10.1.

Metal	*Melting point*		*Potential operating temperature, 2/3 T_m*		*T/T_m actually achieved*
	°C	°K	°K	°C	
Al	660	933	620	350	0.56 (RR58 at 250°C)
Cu	1083	1356	900	630	
Ni	1453	1726	1150	880	0.74 (Nimonic 115 at 980°C)
Fe	1536	1809	1200	930	0.47 (ferritic steel at 575°C) 0.57 (austenitic steel at 750°C)
Ti	1668	1941	1290	1020	~0.4
Zr	1852	2125	1420	1150	
Cr	1900	2173	1450	1180	0.6 could be achieved if Cr could be made sufficiently ductile
Hf	2222	2495	1640	1370	
Nb	2468	2741	1830	1550	0.54 could be achieved if a satisfactory coating could be found
Mo	2620	2893	1923	1650	
Ta	2996	3269	2180	1910	
W	3380	3653	2433	2160	0.76 (electric light filament at 2500°C)

Optional

the nickel is added sufficient chromium to provide oxidation resistance without destroying the face-centred-cubic structure. The first alloy was Nimonic 75, essentially 80/20 Ni/Cr with additions of titanium and carbon for precipitation hardening.

	C	*Cr*	*Ti*	*Ni*
Nimonic 75	0.12	20.0	0.4	bal.

It was then found that a more effective precipitation hardening agent was one based on the FCC phase Ni_3Al, in which titanium can replace some of the aluminium to give $Ni_3(Ti,Al)$, termed gamma-prime, γ'. The first of the turbine blade materials to be strengthened with γ' was Nimonic 80.

	C	*Cr*	*Ti*	*Al*	*Ni*	*Zr*	*B*
Nimonic 80A	0.05	20.0	2.3	1.3	bal.	0.05	0.003

Further improvements were then made by adding cobalt to lower the stacking fault energy of the nickel. The cobalt also provided solid solution strengthening and additions of molybdenum were made for the same purpose.

	C	*Cr*	*Co*	*Mo*	*Ti*	*Al*	*Ni*	*Zr*	*B*
Nimonic 115	0.16	15.0	15.0	3.5	4.0	5.0	bal.	0.04	0.014

Precipitates at the grain boundaries are important in controlling creep rupture ductility and impact resistance. If no carbides are present, grain boundary sliding causes premature failure. On the other hand, continuous films provide easy paths for impact failure. The optimum conditions are provided by discrete globular particles.

Optional

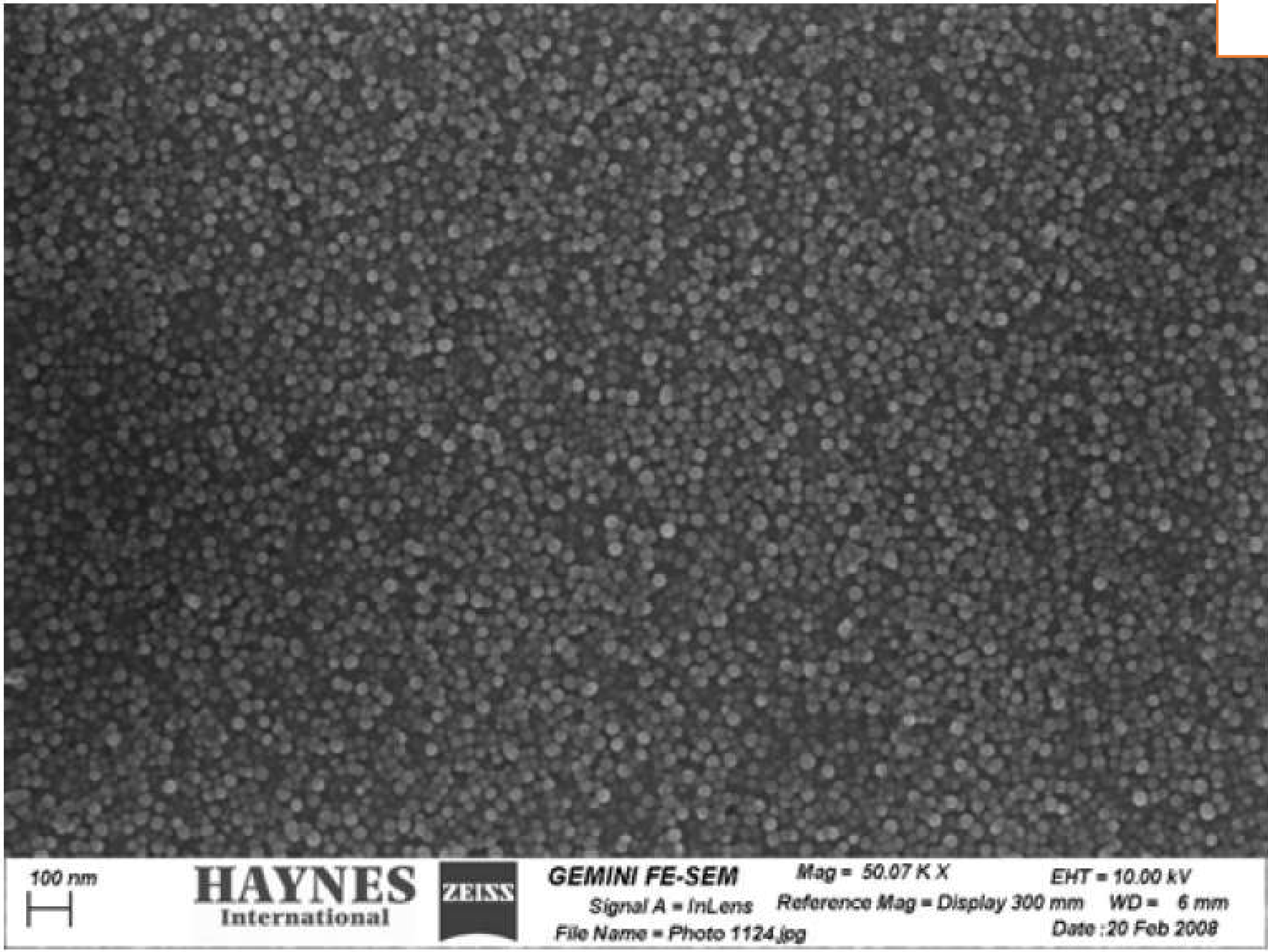

Fig. 4 Gamma-prime phase distribution in 282 alloy

Table I Nominal Composition of Several Wrought Gamma-Prime Alloys (wt.%)

Alloy	Ni	Cr	Co	Mo	Ti	Al	Fe	Mn	Si	C	B	Other
282	57[a]	20	10	8.5	2.1	1.5	1.5*	0.3*	0.15*	0.06	0.005	--
Waspaloy	58[a]	19	13.5	4.3	3	1.5	2*	0.1*	0.15*	0.08	0.006	Zr-0.05
R-41	52[a]	19	11	10	3.1	1.5	5*	0.1*	0.5*	0.09	0.006	--
263	52[a]	20	20	6	2.4*	0.6*	0.7*	0.4	0.2	0.06	0.005	Al+Ti-2.6

[a]As Balance *Maximum

The service temperatures of engineering materials

From the previous section it is clear that although temperature does not alone control creep behaviour it is the most important single factor. It is therefore useful to relate the more important materials to the temperature ranges in which they might be expected to give useful service. The temperatures of interest to the materials engineer range from cryogenic regions, say –200°C (–328°F), up to the operating temperature of a tungsten-filament lamp, say 2000°C (3630°F). For present purposes we need only consider the range from room temperature upwards.

- Room temperature to 150 °C
- 150-400 °C
- 400-600 °C
- 575-650 °C
- 650-1000 °C
- 1000 °C and above

محدوده های دمایی برای خزش

RT-150 °C

- سرب: تنها فلز مهندسی که در تمامی دماهای بالاتر از محیط خزش می کند، کاربرد در سقف ها (roofing) و در قدیم برای مصارف لوله کشی خانگی، به دلیل فرایند ساخت و شکل پذیری بسیار خوب
- آلیاژهای پایه قلع، کاربرد میکرو الکترونیک تا دمای ۶۵-۷۰°C
- ترموپلاستیک ها عمدتا در دماهای کمتر از 70 °C تحمل دارند. تقریبا فقط تفلون است که تا 200°C را نیز تحمل می کند.

150-400 °C

- PTFE تفلون
- برخی آلیاژهای آلومینیم، پیستون موتور برخی خودروها Al-12Si-Cu-Mg تا °C ۲۸۰
- آلیاژ Cu-As (سه عنصر سمی Cd, Be, As در مس بسیار مفید هستند)
- Cu-1Cr ، Cu-0.1Zr ، Cu-1Cr-0.1Zr هدایت الکتریکی، استحکام، کاربرد دمای بالا (حداکثر ۳۵۰°C) و مقاومت به نرم شدن بیشتر (مس خالص از °C ۱۵۰ شروع به نرم شدن)
- فسفر برنز (Cu-Sn حاوی 0.2-0.25 فسفر) - آلومینیم برنز (تا ۳۰۰ حتی °C ۴۰۰)
- Monel metal (Ni-30 Cu-2.5 Fe-2 Mn)
- چدن با گرافیت کروی تا °C ۲۵۰ (For low-pressure turbine casings)- عموما مقاومت به خوردگی چدنها به دلیل لایه پسیو بهتر از فولادهای معمولی است اما در دماهای بالا چدنها به دلیل کربن بالاتر، کربن پس می دهند.
- فولادهای ساده کربنی از لحاظ استحکامی تا °C ۴۰۰ مشکلی ندارند اما از لحاظ خوردگی خیلی ضعیف هستند.

400-600 °C

- آلیاژهای تیتانیم. (سری آلفا مقاومت خزشی بهتری دارند).
- Ti-6Al-4V تا ۴۵۰ °C (بسیار پرکابرد-هوافضا) – رده های حاوی عناصر آلیاژی مانند Zr و Nb تا ۶۰۰ °C هم تحمل می کنند. عموما آلیاژهای تیتانیم بالاتر از ۵۷۵ °C به دلیل اکسیداسیون قابل استفاده نیستند.
- کاربرد آلیاژهای تیتانیم در مواردی که توجیه اقتصادی دارد مانند هوافضا
- فولادهای کم آلیاژ فریتی (FLAS)- piping در نیروگاه ها تا ۵۰۰ °C (Fe-0.2C-1Cr-1Mo-0.25V)
- فولادهای زنگ نزن مارتنزیتی: ابزار برش جراحی، قطعات توربین گاز دما پایین و فشار بالا (۴۰۰-۵۰۰ °C)

In the gas turbine field[18] heat-treatable martensite stainless steels with ~13% chromium have been used in the range 400–500°C (750–930°F) for discs and blades. These steels have a family relationship with modifications to the composition of BS 970 410 (UNS S41000) to maximize specific properties as required, e.g. Cr and Ni may be increased for better corrosion resistance, increased C for improved strength and hardness, increased S and P for machinability, C decreased for improved toughness, Mo, V, W added for strength and toughness at elevated temperature. Within this family come a large number of proprietary steels as instanced by the historic Firth Vickers grades (FV) (see Table 10.4).

TABLE 10.4.

	C	*Cr*	*Ni*	*Mo*	*Nb*	*V*	
FV448	0.10	11.00	0.75	0.70	0.40	0.15	0.05N
FV535	0.07	10.50	0.30	0.70	0.45	0.20	6.00Co
S62	0.25	13.50	0.40	–	–	–	–

575-650 °C

- در این دما نقش اکسیداسیون زیاد است و منجر به تسریع خزش می گردد.

- زنگ نزن C-13Cr-0.5Mo
- می تواند برای پره های توربین بخار دریایی استفاده شود (تا ۵۶۵ درجه سانتیگراد) اما دچار حمله کلریدی ناشی از آب ورودی می گردد.

- زنگ نزن های فریتی ارزانتر از آستنیتی هستند اما مقاومت به خزش و خوردگی آستنیتی ها، برای این محدوده دمایی عملکرد بهتری دارند.

- در زنگ نزن های آستنیتی هرچه درصد کربن کاهش یابد، مقاومت به خوردگی و قابلیت جوشکاری توامان افزایش می یابد.

- AISI 316 (ایمپلنت ها عموما 316L) استحکام خوب و مقاومت به خوردگی بالا

TABLE 10.5.

	C	Si	Mn	Ni	Cr	Mo	Others
304	0.06	0.20–1.00	0.50–2.00	9.0–11.0	17.5–19.0	–	–
304(ELC)	0.03	0.20–1.00	0.50–2.00	9.0–12.0	17.5–19.0	–	–
321	0.08	0.20–1.00	0.50–2.00	9.0–12.0	17.0–19.0	–	–
316	0.07	0.20–1.00	0.50–2.00	10.0–13.0	16.5–18.5	2.25–3.0	Ti 5X C–0.70
347	0.08	0.20–1.00	0.50–2.00	9.0–12.0	17.0–19.0	–	Nb 10X C–1.00

650–1000°C (1200–1830°F)

Three main groups of alloys are available for use in this temperature range: (1) the austenitic stainless steels; (2) the alloys based on the nickel–chromium and nickel–chromium–iron systems; and (3) the cobalt-based alloys.

- آلیاژهای مناسب این دماها دارای پیچیدگی های متالورژیکی بوده و نیز برای بهبود رفتار خزشی، مرزدانه ها باید کمتر باشد (درشت دانه، به سمت تک کریستال): ساختارهای as-cast و نه کار مکانیکی شده.

- کشیدگی دانه ها (جهت انجماد) در راستای طولی پره های توربین

- پوشش دادن Coating

- دمای معادلی وجود دارد که بالاتر از آن برای بهبود مقاومت به خزش، باید دانه ها درشت بوده و پایین آن برای افزایش استحکام باید دانه ریز باشد.

- آلیاژهای پایه کبالت چندان پرکاربرد نیستند (بسیار گران)

- پایه نیکل و پایه نیکل-آهن بسیار پرکاربرد (افزودن آهن سبب کاهش قیمت)

TABLE 10.9. (206 MPa اثر ریزساختار ریختگی بر رفتار خزشی (دما 982 °C درجه سانتیگراد و تنش

	Life (hours)	Elongation (%)	Min. creep rate per hour
Conventionally-cast, equiaxed	35.6	2.6	23.8×10^{-5}
Directionally solidified, polycrystalline	67.0	23.6	25.6×10^{-5}
Directionally solidified, single crystal	107.0	23.6	16.1×10^{-5}

TABLE 10.10. آلیاژهای پایه Ni-Fe (مانند کمپرسور و دیسک توربین)

	C	Cr	Al	Ti	Mo	Fe	B
Incoloy 901	0.05	12.5	0.25	2.8	6.0	42.5	0.015
Inconel 718	0.04	18.6	0.40	0.9	3.1	18.5	–

Coatings

In the main, the discussion here of materials usage in the context of service temperature has been concerned with bulk properties. As temperature rises, and surface attack through mixtures of erosion and corrosion/oxidation becomes significant, there is an increasing requirement for the provision of protective surface coatings such as zirconia. These not only provide specific surface properties in relation to attack, but also introduce a thermal barrier. Such coatings are routinely employed on first stage and some second stage turbine aerofoil components in aero, marine and industrial gas turbines. Nickel-based materials are frequently used as a bond coat onto superalloy components, allowing an outer thermal barrier coating of ceramic. There is also much interest in the use of the intermetallic compounds, NiAl, Ni_3Al and TiAl, for use as coatings at temperatures greater than 1000°C.

1000°C (1830°F) and above

For stressed applications at temperatures above 1000°C it is necessary to look towards (1) the refractory metals, (2) ceramics and, possibly, (3) *in-situ* composites.

The refractory metals

All of the refractory metals, tungsten, tantalum, niobium and molybdenum are available as commercial materials. Tungsten is used universally for electric lamp filaments, and molybdenum is used for radiation shielding of high-temperature furnaces. [redacted] In protected environments these materials can be used at temperatures in excess of 1500°C (2730°F).

- مواد دیرگداز مشکل اکسیداسیون دارند که باید پوشش شوند و در این صورت تا دماهای حدود ۱۵۰۰ درجه سانتیگراد نیز قابلیت کاربرد دارند.

- سرامیک ها مشکل فرایندهای تولید و ساخت را دارند – ماشینکاری بسیار بد

Ceramics

Although the term ceramic must cover materials used for furnace linings, pottery, tiles, etc., engineering interest centres on the more specialized materials known as engineering ceramics. These consist of sintered oxides of aluminium, magnesium, beryllium, zirconium, thorium and certain borides, carbides, nitrides and silicides. They are generally polycrystalline, containing little or no glass phase, and their creep behaviour can be described in terms similar to those that apply to metals. Many ceramics possess high strength at temperatures higher than can be sustained by metals (they can be used under stress up to, or above, 1400°C (2550°F) but, like metals, they are not trouble-free. Carbides and borides tend to oxidize rapidly at temperatures above 1000°C (1830°F). All ceramics are hard and brittle and vulnerable to thermal shock.

- سرامیک ها مشکل فرایندهای تولید و ساخت را دارند
- ماشینکاری بسیار بد
- تافنس پایین و ترد

The most promising ceramics for advanced engineering use are probably silicon carbide, sialon, and silicon nitride. The latter material, having a density of only $3\,Mg/m^3$ and being resistant to oxidation, is a candidate for service temperatures of 1200°C in gas turbines.[20]

Selection for Corrosion Resistance

انتخاب مواد با معیار مقاومت به خوردگی

TABLE 11.1. Galvanic series for metals and alloys in sea water[2]

Noble
Titanium
Monel (67% Ni, 30% Cu, 1.2% Mn, 1.2% Fe) plus C, Si.
Passive stainless steel (18% Cr, 8% Ni) – covered with oxide film
Silver
Inconel (80% Ni, 13% Cr, 6.5% Fe)
Nickel
Copper
α-brass (70% Cu, 30% Zn)
α/β brass (Muntz metal 60% Cu, 40% Zn)
Tin
Lead
Active stainless steel (18% Cr, 8% Ni) – oxide film destroyed
Cast iron
Mild steel
Aluminium
Zinc
Magnesium
Base

Note: This table does not show the metals in quite the same order as one for the standard electrode potential against a reference electrode. This is because of the nature of the oxide film, as shown by the two positions given for stainless steel.

In the case of **two dissimilar metals** joined together we speak of a bimetallic couple and the polarities of the two members of the cell are usefully indicated by their position in the galvanic series (Table 11.1).

For metals that are far apart in the series it may be expected that the **base** reactive member of the couple will **corrode**.

The selection of materials for (resistance to):

- Atmospheric corrosion
- Oxidation at elevated temperatures
- Corrosion in the soil
- Corrosion in water
- Corrosion in chemical plant

11.3 The selection of materials for resistance to atmospheric corrosion

The most significant factor controlling the probability of corrosive attack is whether or not an aqueous electrolyte is likely to be provided by condensation of moisture under prevailing climatic conditions. Clearly, hot, dry or cold, icy conditions give less attack than wet, as does a clean atmosphere as compared to the industrial or marine atmospheres containing sulphur dioxide and salt respectively. Even within given areas, differing microclimates can exist as a function of direction of exposure to sun, wind and polluting sources. In the case of sulphurous acid attack the effect is more noticeable in the winter, when more fuel is burned and conditions are generally wet.

عوامل اصلی:

- میزان رطوبت موجود در اتمسفر
- میزان گازهای موجود
- دما

- اتمسفر عموما بر سطح مواد مهندسی اثر کرده که در بعضی موارد تا عمق قطعه نیز اثر می گذارد.
- معمولا محیط های مرطوب، گازهای خورنده مانند SO_2 و CO_2 و دمای بالا خوردگی را تشدید می کنند.

- فولادهای گالوانیزه (پوشش Zn) در محیط های روستایی خشک تا حدود ۲۰ سال گارانتی دارند و در محیط های صنعتی مرطوب (حاوی SO_2 و CO_2) عمر بمراتب کمتری دارند.
- در اروپا شرایط برای خوردگی اتمسفری بسیار فراهم است.

- **فولادهای ساده کربنی** (constructional) مانند بدنه خودرو، در محیط های صنعتی زنگ می زنند.
- در مناطق شمالی و جنوبی ایران تشدید خوردگی
- معمولا برای مصارف صنعتی فولادهای ساختمانی را در حالت coated استفاده می کنند مانند رنگ زدن، آبکاری، حلبی، گالوانیزه، ...
- بعضی فولادهای mild steels and low alloy تا 0.2%Cu دارند که مقاومت به خوردگی اتمسفری را افزایش می دهد (فولادهای آب و هوایی weathering).
- گاهی اوقات به فولادها 0.2-0.3 Cr اضافه می کنند که سبب تشکیل یک لایه اکسید کرم شده و سالها در اتمسفر معمولی سطح را محافظت می کند و باز هم فولاد صیقلی می ماند (فولاد صیقلی)
- Phosphorus, silicon and chromium present in carbon and low-alloy steels are also considered to improve corrosion resistance, particularly in combination with copper.
- فولادهای کم آلیاژ و ماریجینگ ها نیز مانند فولادهای ساده کربنی، مقاومت مناسبی در برابر خوردگی اتمسفری ندارند.

فولادهای زنگ نزن

- **مارتنزیتی (M):** عمدتا فقط کرم دارند و کربن آنها بالاست. مقاومت به خوردگی خوبی دارند اما باز هم ایده آل و عالی نیستند مانند تیغ های اصلاح – C % 0.1-1 و Cr 12-17% با عملیات حرارتی مارتنزیتی می شوند. سختی و استحکام بالا در مقایسه با فریتی و آستنیتی – AISI 403, 410, 414, 416, 420, 431, 440, 501

- **فریتی (α):** کربن پایین (کمتر از 0.2%) و حدود Cr 11-30% -مقاومت به خوردگی بسیار خوب – زه خودرو در پیکان های قدیمی (بعدها با آلومینیم اکسترود شده جایگزین شد) – غیر قابل عملیات حرارتی – جوشکاری و شکل پذیری خوب – سختی و استحکام نسبتا پایین – AISI 405, 429, 430, 446, 502

- آستنیتی (γ): مقاومت به خوردگی بسیار عالی (بهترین)، معمولا کربن کمتر از 0.15%، Ni 6-22%، 16-25%Cr - AISI 304, 316, 321, 310, 314, 302 – گران قیمت – غیرقابل عملیات حرارتی سختکاری –در حالت آستنیتی جذب مغناطیس نمی شوند (نگیر)- سخت شدن با کار سرد (احتمال تبدیل بخشی از زمینه به مارتنزیت حین کار سرد)- استحکام متوسط

- Duplex
- Precipitation hardening

- **چدن ها:** مانند فولادها اما با نرخ خوردگی اندکی کمتر به دلیل فسفر آنها – در کاربردهای اتمسفری بسیار استفاده می شوند – درپوش چاهک های آب و فاضلاب، سر سیلندر

- **آلیاژهای آلومینیم:**

  - گروه های غیرقابل عملیات حرارتی 1, 3, 5xxx بسیار مقاومت به خوردگی خوب
  - گروه های قابل عملیات حرارتی مقاومت به خوردگی کمتر دارند 2, 6, 7xxx (رسوب سختی برای مقاومت به خوردگی مناسب نیست)– گروه 6xxx بهتر است و برای پروفیل های در و پنجره پرکاربرد است.
  - آنودایز (رنگی): ایجاد یک لایه اکسید چسبنده و سخت سرامیکی و مقاوم به خوردگی (Al_2O_3)

- **آلیاژهای مس:** مس خالص در محیط خشک مشکلی ندارد اما در رطوبت اکسید می شود – در برخی کشورها از مس برای نمای خارجی ساختمان استفاده می شود که بعد از اکسیداسیون نما به رنگ های مایل به زرد و آبی به نظر می رسد.

- آلیاژهای مس تقریبا همگی دچار خوردگی می شوند مخصوصا برنج ها که مشکل روی زدایی دارند (Zn بیشتر از ۱۵٪). بهبود شرایط با افزودن قلع در برنج دریایی 60Cu-39.25Zn-0.75Sn.

- در آلیاژهای مس هر چه به سمت برنزها برویم وضعیت بهتر می شود مانند برنز آلومینیم و برنز منگنز که کاربرد دریایی دارد.

- **سرب و روی (Pb , Zn):**

- روی از بهترین ها برای کاربردهای مقاوم به خوردگی اتمسفری است، پوشش بر روی فولاد (گالوانیزه) نقش آند فدا شونده (در مقابل پوشش قلع بر روی فولاد -حلبی- که در صورت خراش برداشتن فولاد خورده می شود)

- سرب از روی نیز بهتر است – در قدیم گاهی اوقات پشتبان را با ورق های بسیار نازک سرب اندود می کردند (تا سالیان بسیار طولانی water proof)

- سرب در مقابل اسیدها بسیار مقاوم است. بطور کلی سرب و سرامیک ها برای اسیدهای بسیار قوی و نگهداری آنها قابل استفاده هستند.

11.4 The selection of materials for resistance to oxidation at elevated temperatures

Whilst traditionally corrosion has been treated on a 'wet' and 'dry' basis, 'dry' oxidation corrosion can be considered as an electrolytic process of an interfacial anode/cathode type (see p. 146). Since the corrosion rate is governed by the transport of ions and electrons through the produced film, equatable to a current, it is clear that the oxidation rate will be low where the oxide film has a high electrical resistance and where it is not prone to mechanical rupture.

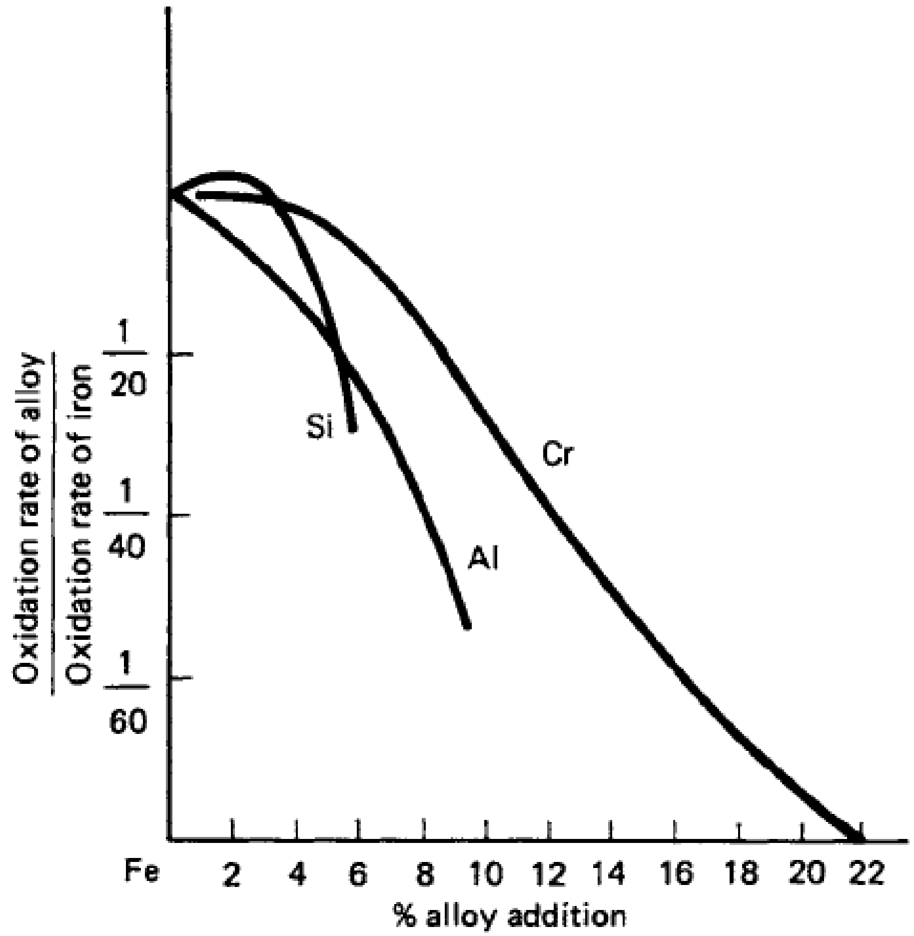

Figure 11.6 Effect of silicon, aluminium and chromium on the oxidation rate of iron at 900–1100°C. (Shreir[1], after Kubaschewski and Hopkins[8])

- مهم اینست که لایه اکسیدی که تشکیل می شود آیا می تواند بقیه ماده را از تماس با محیط حفظ کند یا خیر؟ سینتیک تشکیل لایه اکسیدی چقدر است؟

- کروم هم براحتی اکسید نمی شود و هم لایه اکسید آن پیوسته و محافظ خواهد بود.

- بر اساس منحنی ارائه شده، کروم می تواند خوردگی آهن را تقریبا به صفر برساند.

- چدن ها از لحاظ مقاومت به اکسیداسیون دمای بالا، کمی بهتر از فولادهای معمولی هستند (به دلیل اجزای ساختاری مانند یوتکتیک فسفید آهن و گرافیت). البته در دمای بالا ممکن است، اکسیداسیون داخلی گرافیت موجود در چدن، سبب تورم، بادکردگی و تغییر ابعادی آن گردد.

- هر چه سیلیسیم چدن بیشتر باشد مقاومت به اکسیداسیون دمای بالا بهتر می گردد مانند چدن های با 6% Si. (Silal cast iron: Fe-2.5C-6Si)

11.5 The selection of materials for resistance to corrosion in the soil

The aggressiveness of soils can vary substantially. First, the texture of the soil governs the access of the air necessary for the corrosive process and, second, the presence of water is required for the ionization of the mineral in the soil and the oxidation product at the metal surface. The amount of water present can, of course, also affect the availability of oxygen.

- خوردگی زیر خاک برای لوله های آب و فاضلاب، کابل ها، اجزای حفاری و ... دارای اهمیت است.
- جنس خاک از فاکتورهای بسیار مهم است: هر چه رطوبت و اکسیژن موجود در خاک کمتر باشد، خوردگی کمتری رخ می دهد. بهترین شرایط در خاک های ماسه ای خشک.
- وجود نمک محلول در خاک شرایط را نامساعد می کند.
- اخیرا برای لوله کشی زیر خاک از پلیمرها استفاده می شود. پلاستیک ها تقریبا از لحاظ خوردگی زیر خاک هیچ مشکلی ندارند. در صورت قرارگیری زیر نور آفتاب، نور ماورای بنفش (UV) زنجیره های آنها را پاره کرده و موجب تخریبشان می شود.

11.6 The selection of materials for resistance to corrosion in water

The corrosion of materials in water depends, of course, on the substances that are dissolved, or suspended, in it and also upon its temperature. Dissolved oxygen is most important since in neutral solutions it must be reduced at the cathode for the corrosion reaction to proceed, and it also accounts for the development of passivating oxide films, where these can be produced. Since oxygen enters the system by dissolution from the air, its concentration in large masses of water can vary appreciably both in terms of flow and depth.

Carbon dioxide dissolved in natural water is usually associated with calcium carbonate or bicarbonate. Where the dissolved carbon dioxide is not high enough to maintain the bicarbonate state in solution, the change in pH at cathodic areas will cause the carbonate to precipitate on to the metal surface and if the 'fur' so produced is adherent, further corrosion will be restricted. 'Soft' waters, usually derived from upland open reservoirs of low carbonate content, are therefore more aggressive, particularly since they often contain organic acids deriving from moss and peat which give a low pH.

Other dissolved salts can, of course, have very important effects, and this is particularly significant in the case of sea water, where the chloride ions present decrease the electrical resistivity of the water, so that corrosion currents will be larger. As discussed in relation to passiva-

- بطور کلی آب خورنده است. نوع آب در میزان خوردگی بسیار موثر است. عواملی مانند اکسیژن محلول در آب، PH و ترکیبات آب

- عموماً آب هایی که در صنایع استفاده می شوند مانند صنایع نیروگاهی، عملیاتی روی آنها صورت می گیرد که ترکیبات و PH آنها کنترل شده است (هزینه بالایی دارد). خوردگی در آب دریا به دلیل وجود نمک ها، چندین برابر آب معمولی است.

- آب مقطر خورنده است زیرا $PH = 7$ بوده و با اندکی تغییر اسیدی می شود ($PH < 7$).

- رسوب هایی که در کتری و سماور تشکیل می شوند عموما ترکیبات سولفاتی و کربناتی هستند که در ادامه سطح را از خوردگی محافظت می کنند.

- هر چه اکسیژن آب بیشتر باشد خوردگی بیشتر خواهد بود. تلاطم آب سبب افزایش اکسیژن آب می گردد.

- مقاومت به خوردگی چدن ها نسبت به فولادهای ساده کربنی و کم آلیاژ اندکی بهتر است. وجود 3%Cr در فولاد نرخ خوردگی آن را در آب کاهش می دهد.

- به علت وجود کلر در آب فولادهای زنگ نزن نیز دچار pitting می شوند مگر آنهایی که آستنیتی مولیبدن دار هستند (مانند AISI 316).

Aluminium

Aluminium and its alloys do not corrode in pure water, although they may stain somewhat in natural fresh water, and only those containing copper as a major alloying element will corrode significantly in normal sea water. For freedom from localized pitting associated with the most aggressive sea water conditions (pollutants, etc.) the Al–Mg alloys offer the best choice.

- آلیاژهای آلومینیم سری 1, 3, 5xxx در مقابل آب بسیار مقاوم به خوردگی هستند. بسیاری از قایق های تندرو و کشتیهای کوچک را از سری 5xxx می سازند هم مقاومت به خوردگی خوب و هم جوش پذیری عالی دارند.

- آلیاژهای آلومینیم سری 2, 7xxx (قابل عملیات حرارتی) مقاومت به خوردگی مناسبی ندارند و حفره دار می شوند (pitting).

Copper and copper alloys

These have a traditional and extensive use in the handling of natural waters. Copper is widely used for distributing cold and hot water both in domestic installations and industrial plant, and a wide range of copper-based alloys are employed for such items as tubes for condensers in power stations and desalination plant, and for propellers, valves, pumps, etc.

The inclusion of aluminium in brasses for sea water service (e.g. 76% Cu, 22% Zn, 2% Al, 0.04% As) greatly improves resistance to impingement attack, presumably through modification of the oxide film, making it more tenacious and impervious by the incorporation of alumina. Cupro-nickels and tin bronzes both have generally good resistance to impingement attack and the former are widely used in aggressive conditions at high water velocities.

- مس خالص برای مصارف دریایی و آبی بسیار خوب است. در انگلستان بسیاری از لوله کشی های داخل ساختمان از مس است که عمر بسیار بالایی خواهد داشت. در ایران عموما از فولاد پوشش دار (بیشتر گالوانیزه) و اخیرا پلیمرها استفاده می شود (مس بسیار گرانتر از فولاد است).

- اکثر آلیاژهای مس نسبت به مس مقاومت به خوردگی کمتری دارند. در صنایع آب شیرین کنی یا باید مس خالص باشد و یا برنج هایی با ترکیبات خاص مثلا Admiralty Brass (70Cu-29Zn-1Sn) که به عنوان لوله کندانسور نیز کاربرد دارد.

- مشکل اصلی برنج ها (آلیاژهای Cu-Zn) در آب و رطوبت، **روی زدایی (Dezincification)** است که در آلیاژهای حاوی **بیش از ۱۵٪ روی**، اتفاق می افتد و طی آن عنصر روی از داخل محلول جامد (آلیاژ) خارج شده و آنچه می ماند فلزی متخلخل و با خواص مکانیکی ضعیف خواهد بود. این مشکل را با اضافه کردن برخی عناصر مانند آرسنیک و قلع به برنج، برطرف می کنند.

Nickel

Nickel and nickel alloys are generally resistant to corrosion in fresh water, except under conditions of high acidity and stagnant conditions where the passive oxide film cannot be maintained. The same principle applies in sea water, attack being low (~0.01 mm/y) in neutral chloride-containing environments where the oxygen supply is adequate through active flow conditions in relation to the metal surface. Widely used alloys for marine service are the nickel-copper series (Monel) and nickel-chromium. Both have the particular advantage for pumps, valves, etc. in sea water that the passive film is tough and resists turbulent, high-velocity flow conditions, i.e. they are resistant to impingement and erosion attack.

- نیکل و آلیاژهای آن مقاومت به خوردگی در آب بسیار خوبی دارند. سری آلیاژهای نیکل-مس (Monel) و نیکل-کروم برای کاربردهای دریایی بطور گسترده استفاده می شوند.

- روی (Zn) نسبتا خوب است مخصوصا به عنوان یک پوشش و آند فداشونده در مقابل خوردگی یک فلز پایه مانند فولاد.

11.7 The selection of materials for chemical plant

- در کارخانجات شیمیایی شرایط بسیار خورنده تر و مهاجم تر (aggressive) بوده و اکثر مواد مهندسی مقاوم نیستند. پوشش های غیر فلزی می توانند مفید باشند.

- چدن های آستنیتی (نیکل بالا) و پر کروم و حاوی سیلیسیم می توانند برای صنایع شیمیایی و دمای بالا استفاده شوند.

TABLE 11.2. Analysis of selected number of failures in petroleum related industries (Kermani[14])

Type of failure	*Frequency (%)*
Corrosion (all types)	33
Fatigue	18
Mechanical damage/overload	14
Brittle fracture	9
Fabrication defects (excluding welding defects)	9
Welding defects	7
Others	10

TABLE 11.3 Cause of corrosion related failure in petroleum related industries (Kermani[14])

Type of failure	*Frequency (%)*
CO_2 related	28
H_2S related	18
Preferential weld	18
Pitting	12
Erosion corrosion	9
Galvanic	6
Crevice	3
Impingement	3
Stress corrosion	3

- در بین فولادهای زنگ نزن کمترین مقاومت به خوردگی، مربوط به مارتنزیتی ها (بگیر-مغناطیس شونده) می باشد و کاربرد بیشتر استحکامی دارند مانند پره های توربینی که نیازمند استحکام بالا و دمای نه چندان بالا باشند.

- بهترین مقاومت به خوردگی مربوط به فولادهای زنگ نزن آستنیتی (نگیر- غیرمغناطیسی) می باشد. AISI 316 از این دسته است که نوع کم کربن آن (AISI 316L) به عنوان ایمپلنت های داخل بدن بسیار پرکاربرد هستند که بسیاری مواقع به آنها به اشتباه (!) پلاتین گفته می شود. استحکام دهی این نوع زنگ نزن ها از طریق کارسرد صورت می گیرد.

- در صنایع شیمیایی از فولادهای کم کربن با پوشش های اپوکسی می توان استفاده نمود. گاهی اوقات از لعاب کاری (enameling) و پوشش های سرامیکی برای محافظت در مقابل مواد شیمیایی خورنده استفاده می شود.

- تفلون مقاومت به مواد شیمیایی بسیار بالایی دارد.

- گاهی اوقات فولادهای کربنی را آستر شیشه ای، پلاستیکی یا لاستیکی می دهند

glass-lined, plastics-lined, rubber-lined

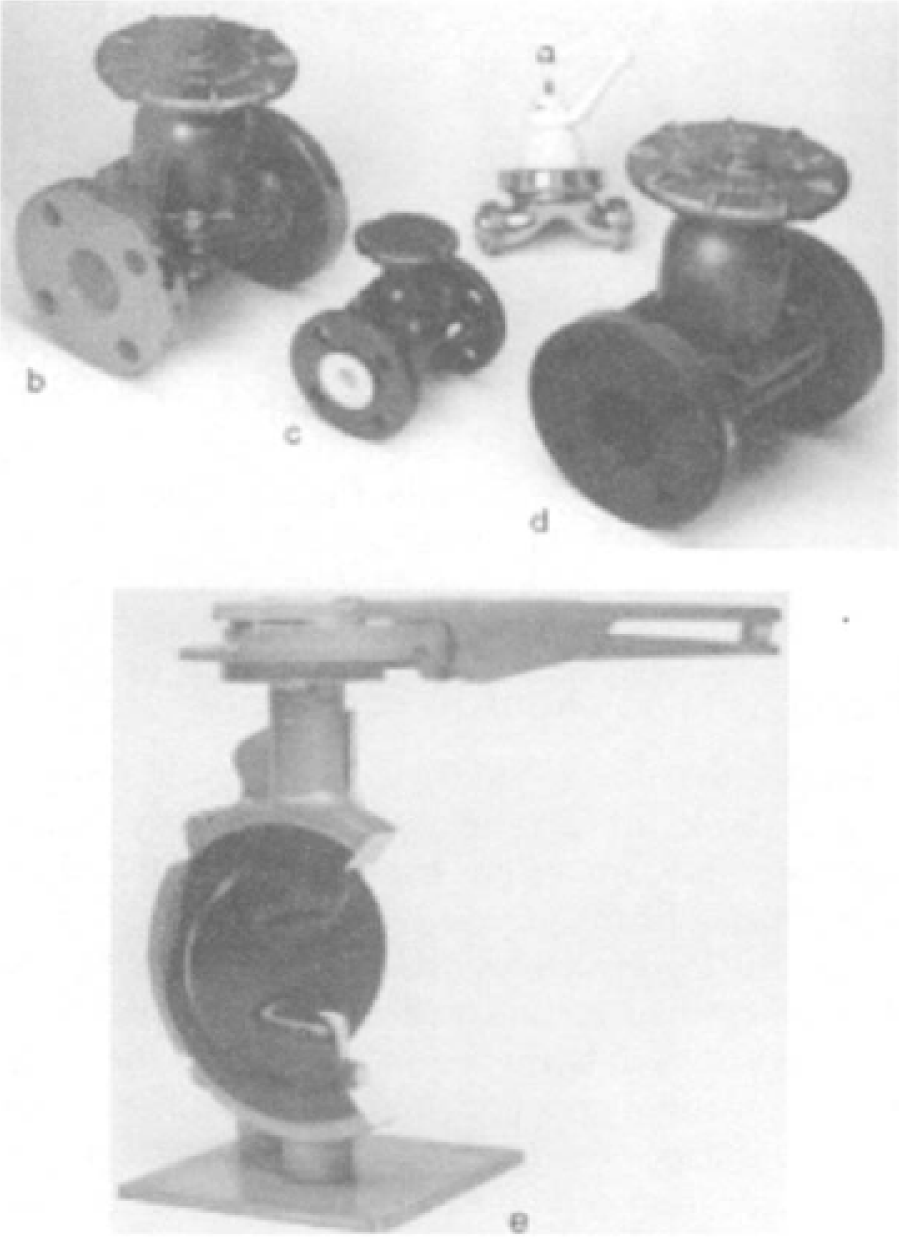

Figure 11.9 Diaphragm valves for varying service: (a) stainless steel; (b) glass-lined; (c) plastics-lined; (d) rubber-lined; (e) butterfly type. (By courtesy of Saunders Valve Co. Ltd.)

Selection and Use of Engineering Materials;

(J.A. Charles, F.A.A. Crane & J.A.G. Furness; Butterworth-Heinemann *)*

« و اینکه برای انسان بهره‌ای جز سعی [و کوشش] او، نیست » (سوره مبارکه نجم، آیه ۳۹)

اَللّٰهُمَّ ما بِنا مِنْ نِعْمَةٍ فَمِنْكَ

بارالها؛ هر نعمتی که بر ماست، از آن توست

با آرزوی موفقیت روز افزون شما

❋ دکتر محمود سمیع زاده ❋