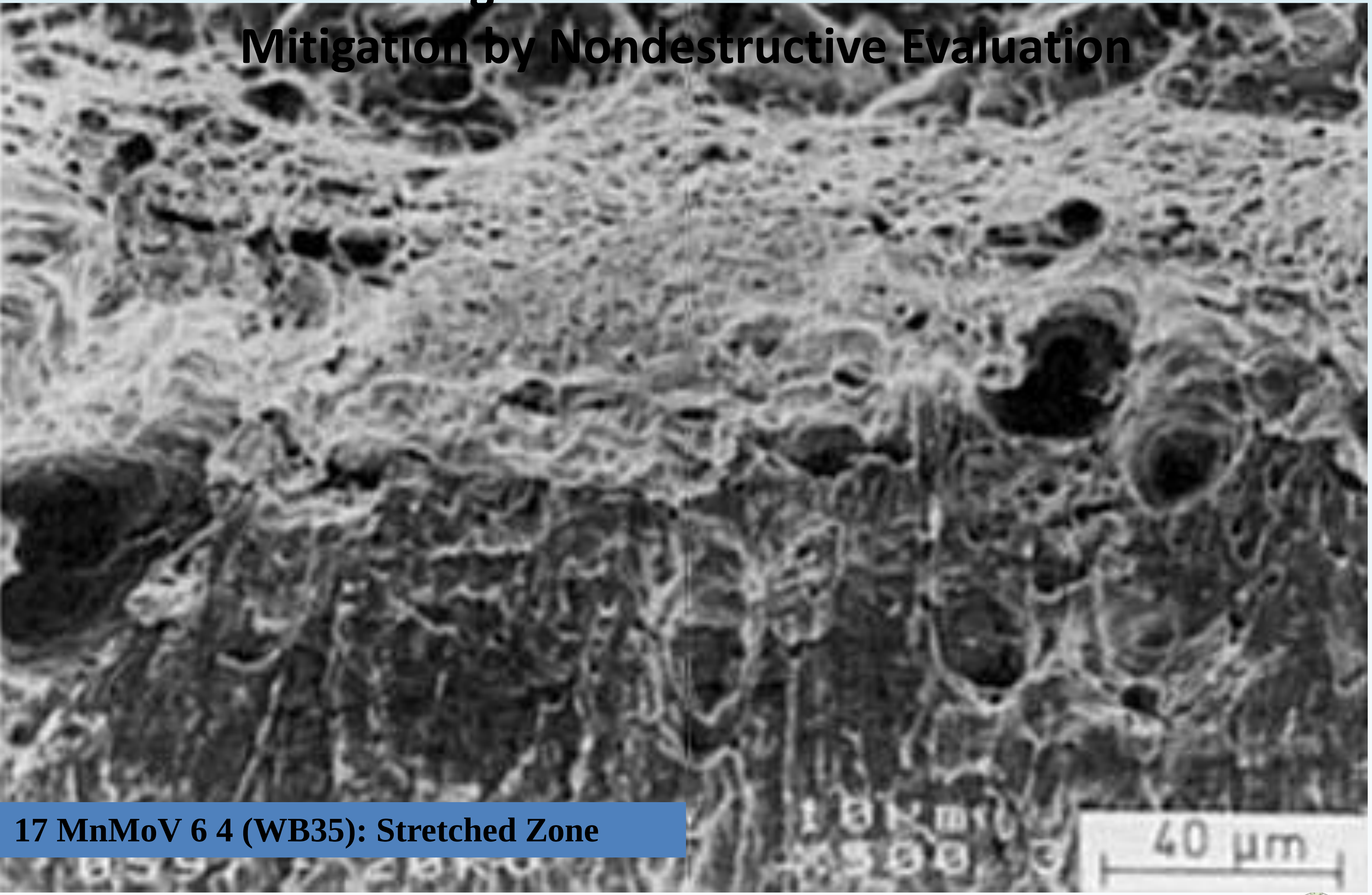
Material Degradation of Nuclear Structures
Mitigation by Nondestructive Evaluation



17 MnMoV 6 4 (WB35): Stretched Zone

Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

STEELS – There are so many

USAGE

Deep drawing steel	Low carbon steel strip with a microstructure to enable it to be extensively pressed or drawn without tearing or failure
Silicon steel	Another term for electrical steel - steel with particular electrical and magnetic properties that makes it especially suited to use in cores of electrical transformers, electrical motors, generators etc
Stainless steel	An alloy of carbon and iron that has a minimum chromium content of 10.5 percent
Structural steel	Construction material formed with a specific shape or cross section certain; it complies with standards of chemical composition and mechanical property requirements
Tool steel	Carbon and alloy steels that have high resistance to abrasion. They are well suited to the manufacture of tools

STEELS – There are so many
Composition

Austenitic steel	Austenitic steels have austenite as their primary phase (face centered cubic crystal). These are alloys containing chromium and nickel (sometimes manganese and nitrogen)
Ferroalloy	Alloy of iron with high proportion of an element such as nickel, chromium, molybdenum, vanadium, etc that used in the production of steel
Interstitial-free	Interstitial-free (IF) steels have few solute interstitial elements, such as carbon and nitrogen. These interstices can be sources of strain and may result in brittleness
Killed steel	Steel that has its oxygen content reduced - typically through addition of aluminium. Hence the term aluminium killed
Mild steel	Low carbon steel - often also referred to as soft steel. Carbon content generally under 0.25%
Wrought iron	Iron that has a low carbon content (usually les than 0.15 per cent). Many traditional applications of wrought iron now use low carbon steel instead

Focus on Steel

There are so many steel grades

commercial grade steel

forging grade steel

structural grade carbon steel

high-grade steel

and many more

CODES & NUMBERS

designating

Intended Use & Chemical Composition

Focus on Steel – Steel Grades & Numbers

STILL CONFUSING

A number of standards organizations has developed steel grades to classify steels by their composition and physical properties.

They are rather different

International Organization for Standardization ISO/TS 4949:2003

European standards - EN 10027

US standards: Unified numbering system (UNS) of ASTM International & the Society of Automotive Engineers (SAE).

SAE steel grades (USA)

British Standards

Japanese steel grades : Japanese Industrial Standards (JIS) standard

Germany steel grades : DIN standard

China steel grades : GB standard

Russian steel grades: GOST standard

and others

Focus on Steel – Steel Grades & Numbers

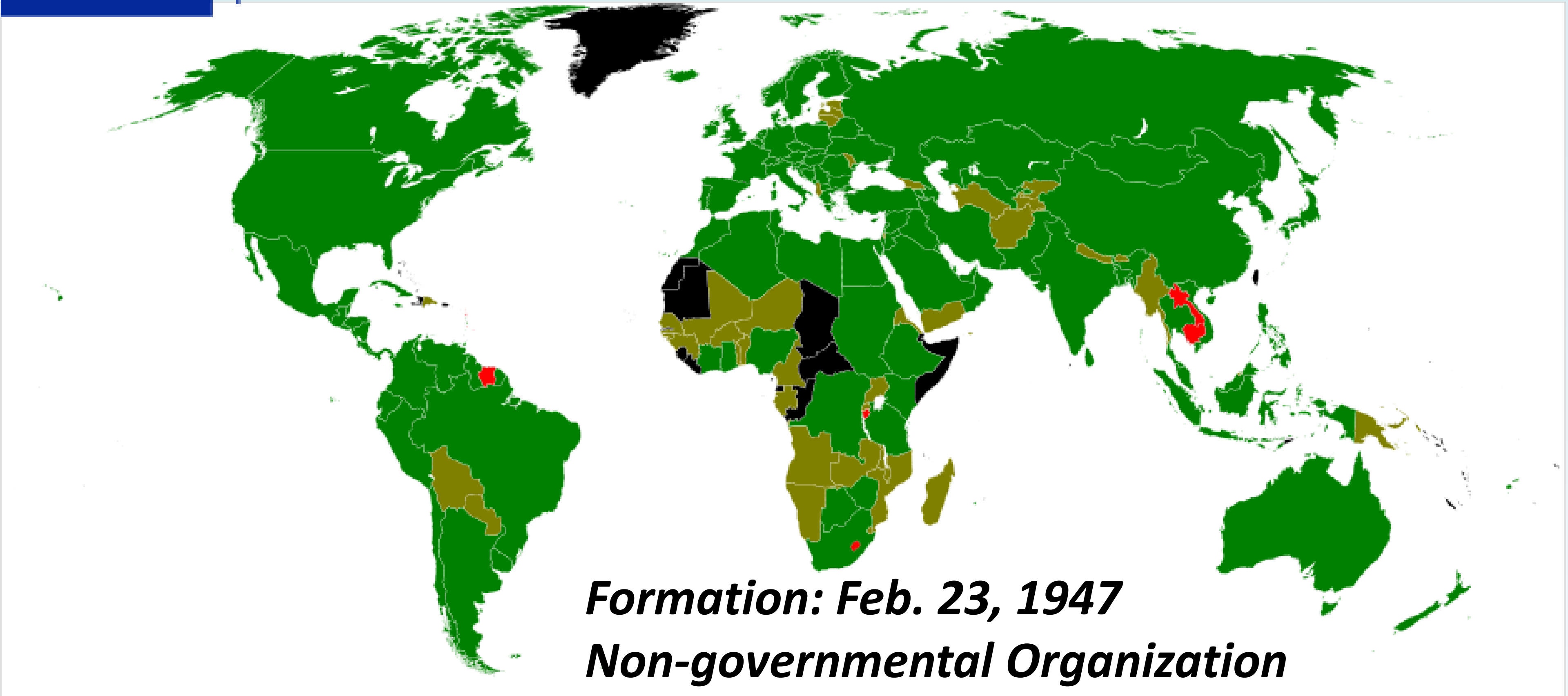
GOST Steel Grade Analogues
(nearest equivalents - chemical composition)

Russian GOST	American AISI, ASTM, ASME	German DIN	Japanese JIS	Great Britain B.S	Italian UNI	French AFNOR NF
03X17H14M3	316L SA-240TP316L	X2CrNiMo18-14-3	SUS 316L	316S13 LW 22	X2CrNiMo18-14-3 X2CrNiMo1713KG	Z3CND1712-03
03X18H11	304 L SA-240TP304L	X2CrNi1911 GX2 Cr Ni 19-11	SUS304 L	304S11 LW 20 LWCF20 S536304 C12 (LT 196) 305 S 11	X2 CrNi 18 11 X 3 CrNi 18 11 GX 2 CrNi 19 10	Z1CN18-12 Z2CN18-10 Z 3CN19-10M Z3CN18-10 Z3CN19-11 Z3CN19-11FF
03XH28МДТ 06X28МДТ	?	X3NiCrCuMoTi273 0	?	?	?	?
06X18H11	305 3008	X4CrNi18-12	SUS 305 SUS 305J1	305S17 305S19	X7CrNi18 10 X8CrNi 19 10	Z 5

International Organization for Standardization

Steel Grades

ISO/TS 4949 (2003)



Formation: Feb. 23, 1947

Non-governmental Organization

International Standardization

Geneva, Switzerland

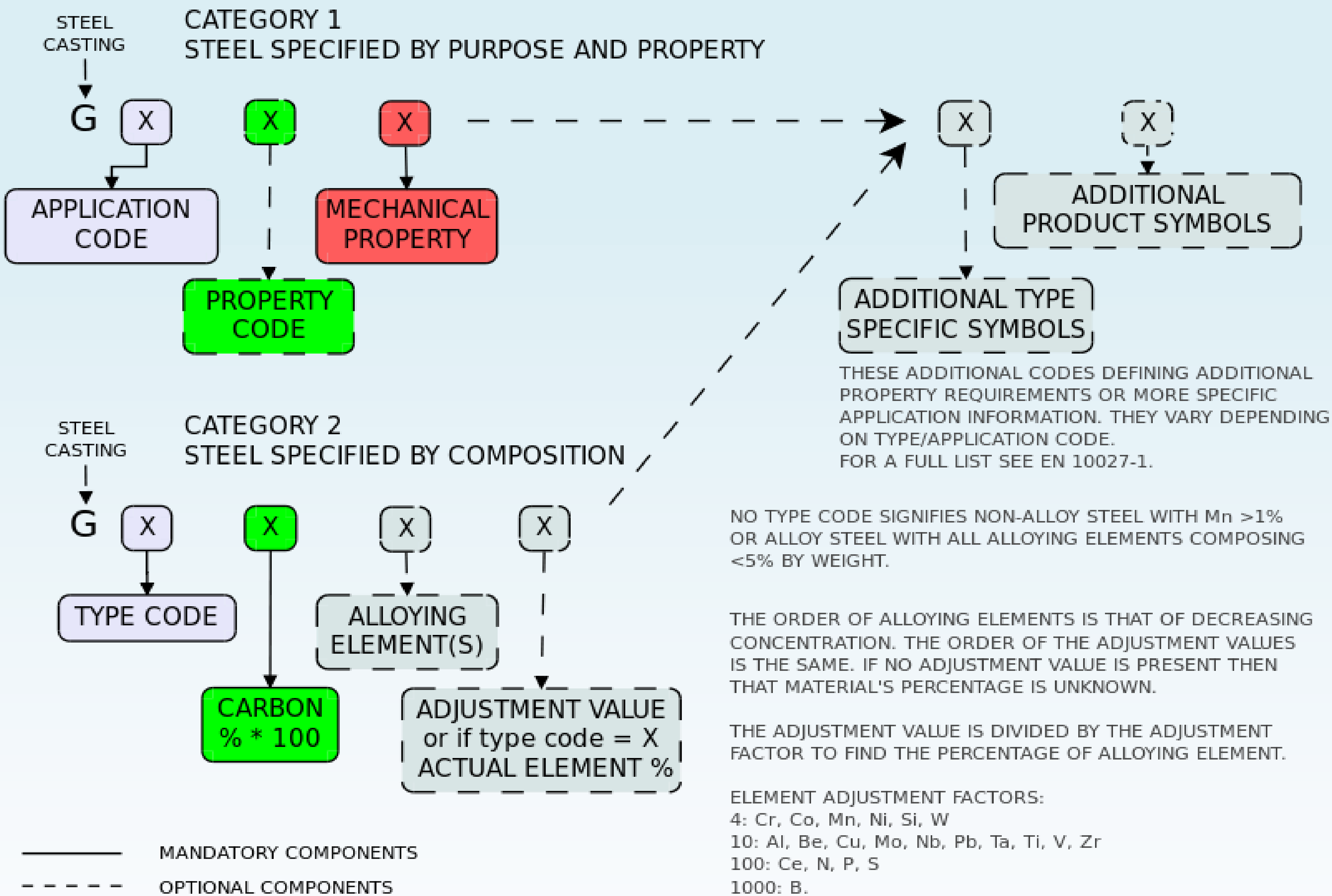
English, French, Russian

European Standards

Steel Grades: EN 10027

EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

EN 10027-1 steel grade designation system



Basic steel grade designations for category 1 steels

most common application codes

BY PURPOSE:

DIN EN 10027-1

Application Symbol	Meaning	Mechanical Property	Details
S	Structural steel	M Y S[1]	1) Minimum yield strength
P	Pressure lines and vessels	M Y S	
L	Pipe and tube	M Y S	
E	Engineering steels	M Y S	
B	Steel for reinforced concrete	C Y C[2]	2) Characteristic Yield Case
R	Steel for rail use	M Y C[3]	3) Minimum Yield Case
H	High Strength Cold Rolled	M Y C	
D	Flat Products for Cold Forming		followed by C, D or X and two numbers characterising steel
T	Tinmill Products	N Y C[4]	4) Nominal Yield Case

Additional symbols for structural steels category 1 - Sxxx.

Impact resistance codes

Impact code	Testing strength
J	27 J
K	40 J
L	60 J

Temperature codes

Temperature code	Testing temperature
R	Room temp.
O	0°C
2	-20°C
3	-30°C
4	-40°C
5	-50°C
6	-60°C

+20	0	-20	-30	-40	-50	-60	
JR	J0	J2	J3	J4	J5	J6	27 J
KR	K0	K2	K3	K4	K5	K6	40 J
LR	L0	L2	L3	L4	L5	L6	60 J

Delivery condition codes

Code	Condition
A	Annealed
QT	Quenched and tempered
N	Normalized
SR	Stress relieved
C	Cold worked
M	Thermo mechan. rolled
Q	Tempered
U	Untreated

S235JR+C

S: steel for steel construction

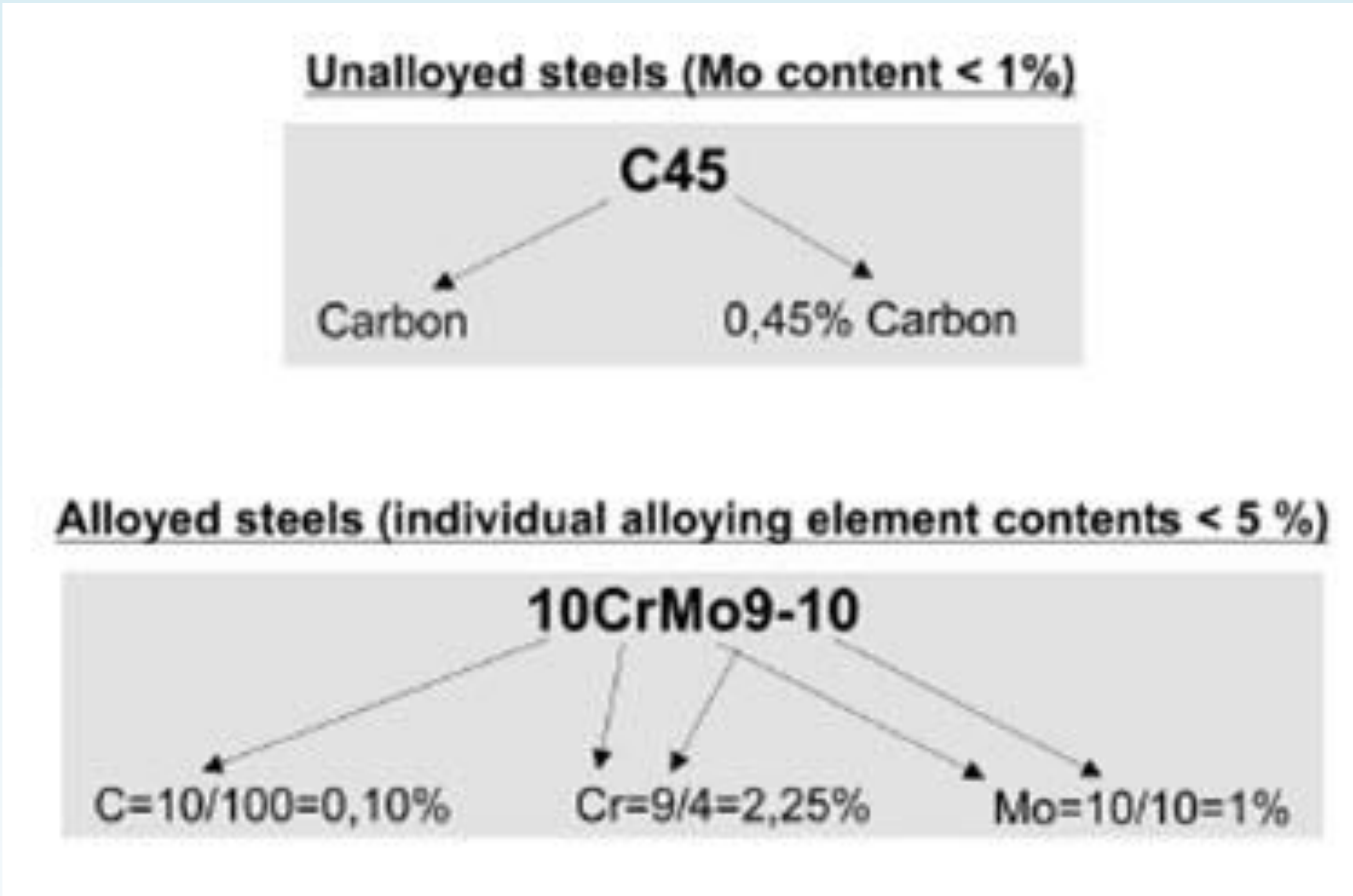
235: SMYS 235 N/mm^2

JR = 27J notch impact strength 20 °

C = cold rolled

Focus on Steel – Code designation

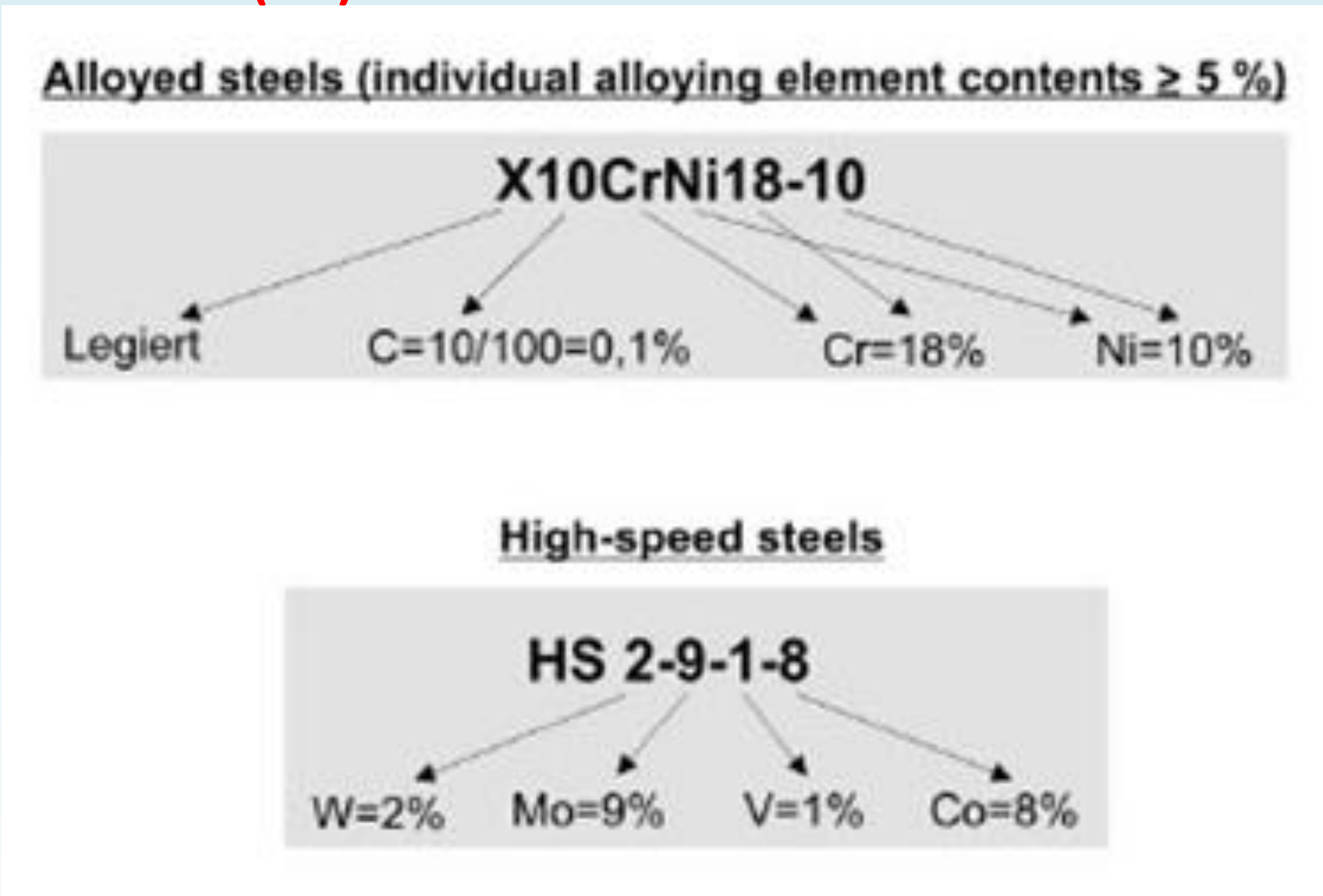
BY COMPOSITION (EN)



Code designation
according to chemical composition

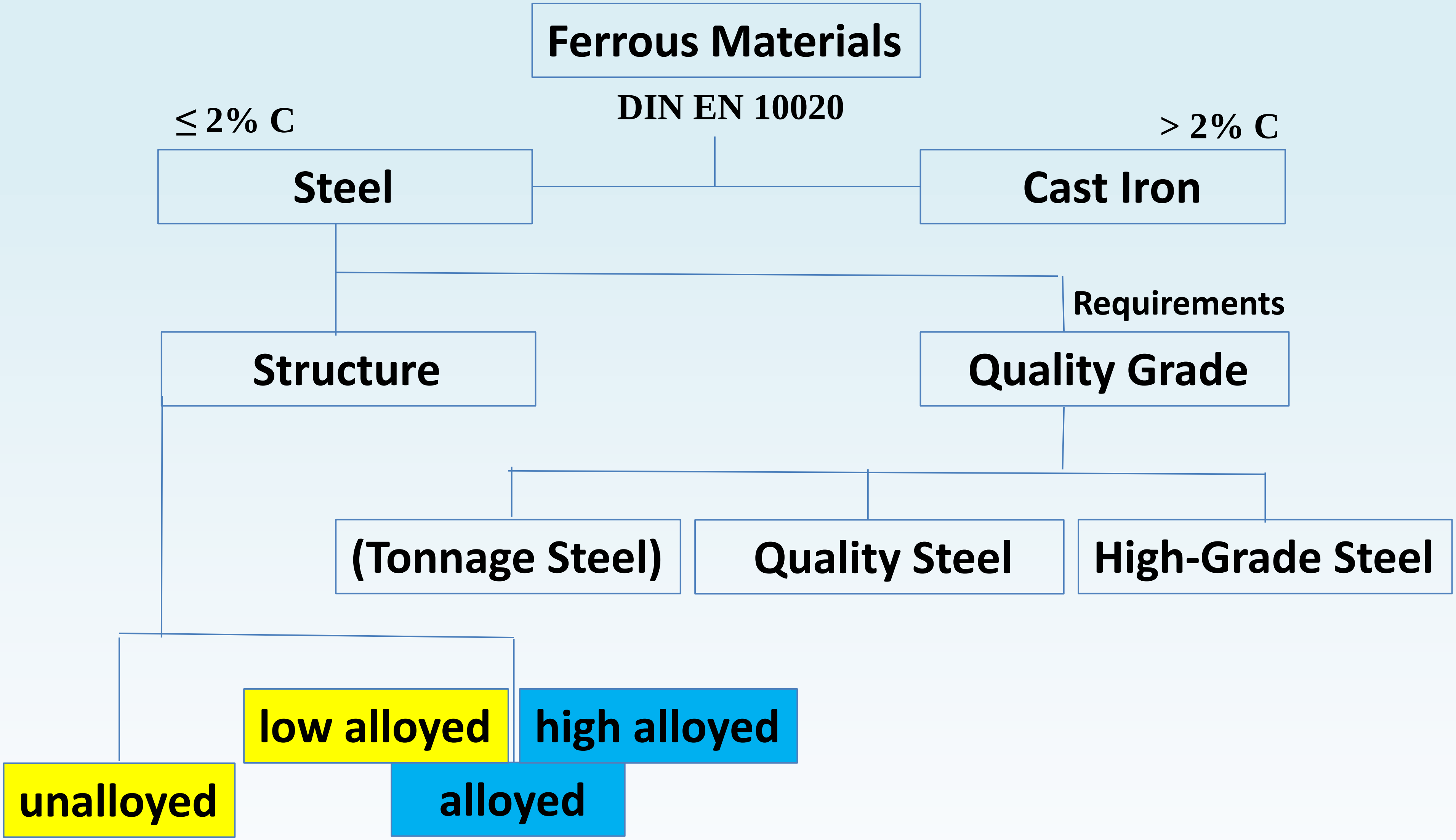
Focus on Steel – Code designation

BY COMPOSITION (EN)



Code designation
according to chemical composition

Focus on Steel – Carbon Steels



Carbon Steels

These are steels in which the main interstitial alloying constituent is
carbon in the range of 0.12–2.0%.

The American Iron and Steel Institute (AISI) defines carbon steel as the following:
"Steel is considered to be carbon steel when no minimum content is specified or required for

- **chromium,**
- **cobalt,**
- **molybdenum,**
- **nickel,**
- **niobium**
- **titanium,**
- **tungsten,**
- **Vanadium**
- **Zirconium**

or any other element to be added to obtain a desired alloying effect;

when the specified minimum for copper does not exceed 0.40 percent;

or when the maximum content specified for any of the following elements does not exceed the percentages noted:
manganese 1.65, silicon 0.60, copper 0.60."

Carbon Steels

Limit Values for Alloy Elements

Al	B	Bi	Co	Cr	Cu	La	Mn	Mo	Nb	Ni	Pb	Se	Si	Te	Ti	V	W	Zr	
0,3	0,0008	0,1	0,3	0,3	0,4	0,1	1,65	0,08	0,06	0,3	0,4	0,1	0,6	0,1	0,05	0,1	0,3	0,05	%

Unalloyed Steels

No Alloy Element exceeds its Limit Value

Alloyed Steels

At least one Alloy Element exceeds its Limit Value

low alloyed

high alloyed

At least one Alloy Element exceeds 5%

Focus on Steel – Carbon Steels

Four classes of Carbon Steel (Defined by carbon content)

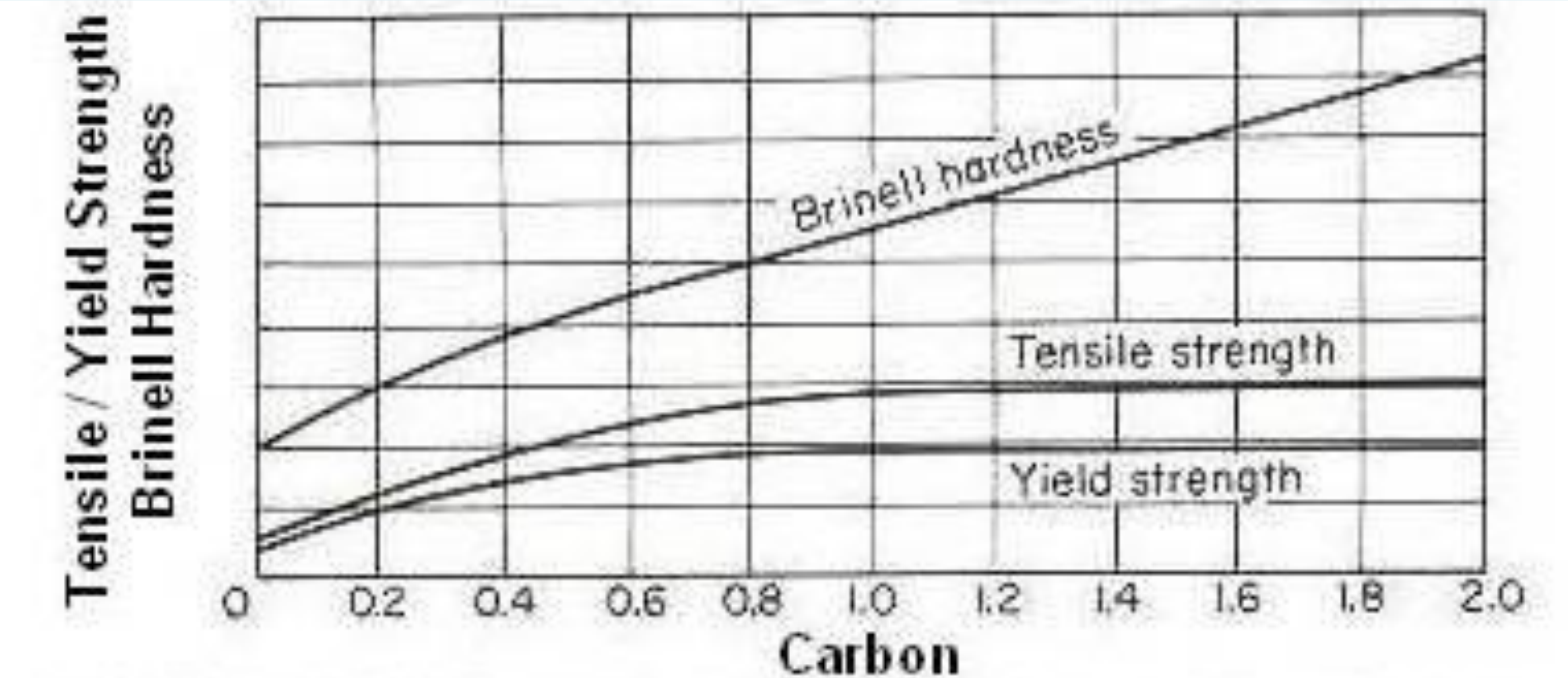
Mild (plain-carbon) and low-carbon steel (0.05–0.32 weight% C)

Medium carbon steels (0.30–0.59 weight% C)

High-carbon steels (0.60–0.99 weight% C)

Ultra-high-carbon steel (1.0–2.0 weight% C)

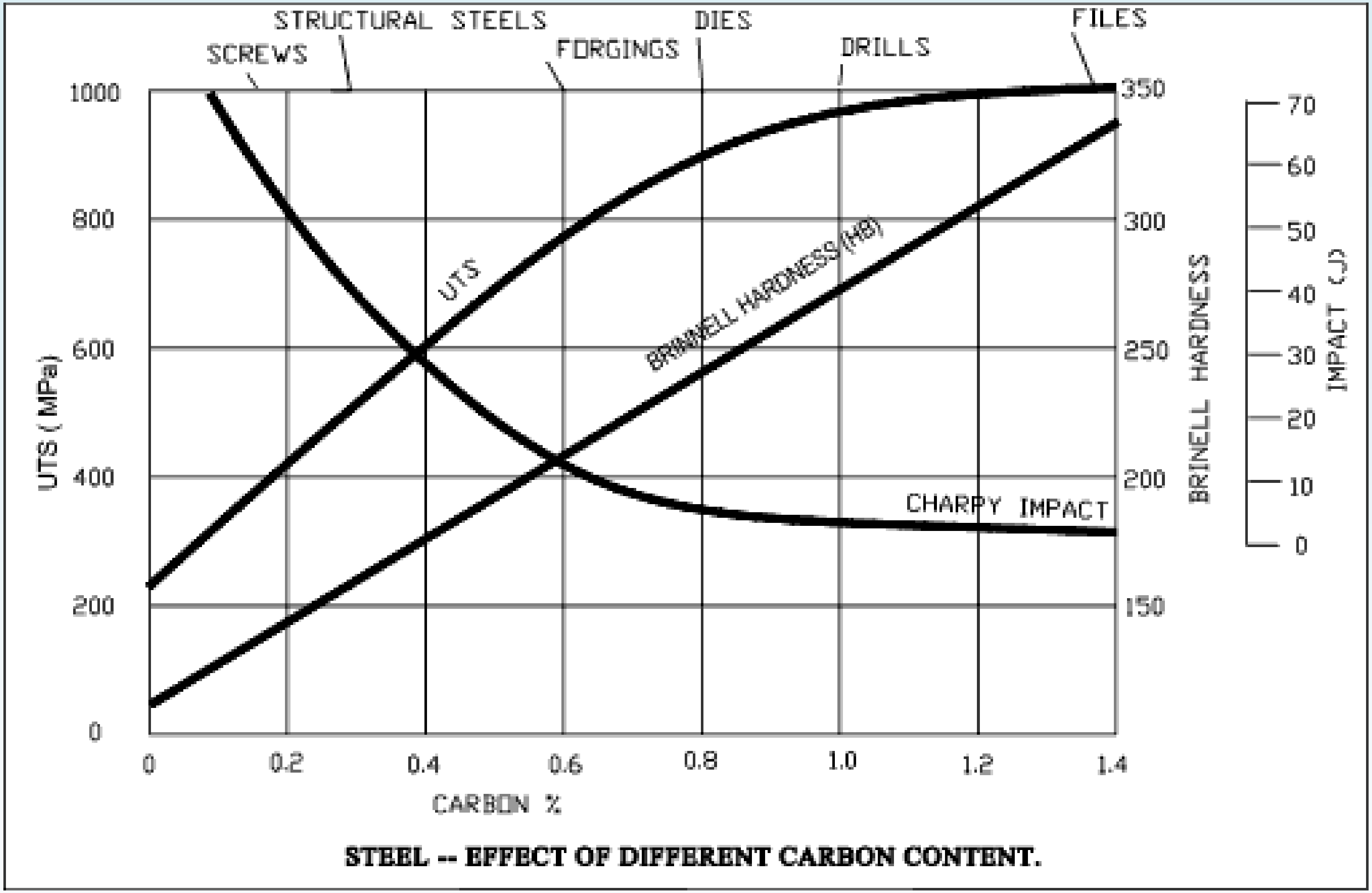
Focus on Steel – Carbon Steels



Effect of Carbon on Mechanical Properties of Steel

Focus on Steel – Carbon Steels

STRENGTH/HARDNESS ⟷ TOUGHNESS



Focus on Steel – Carbon Steels

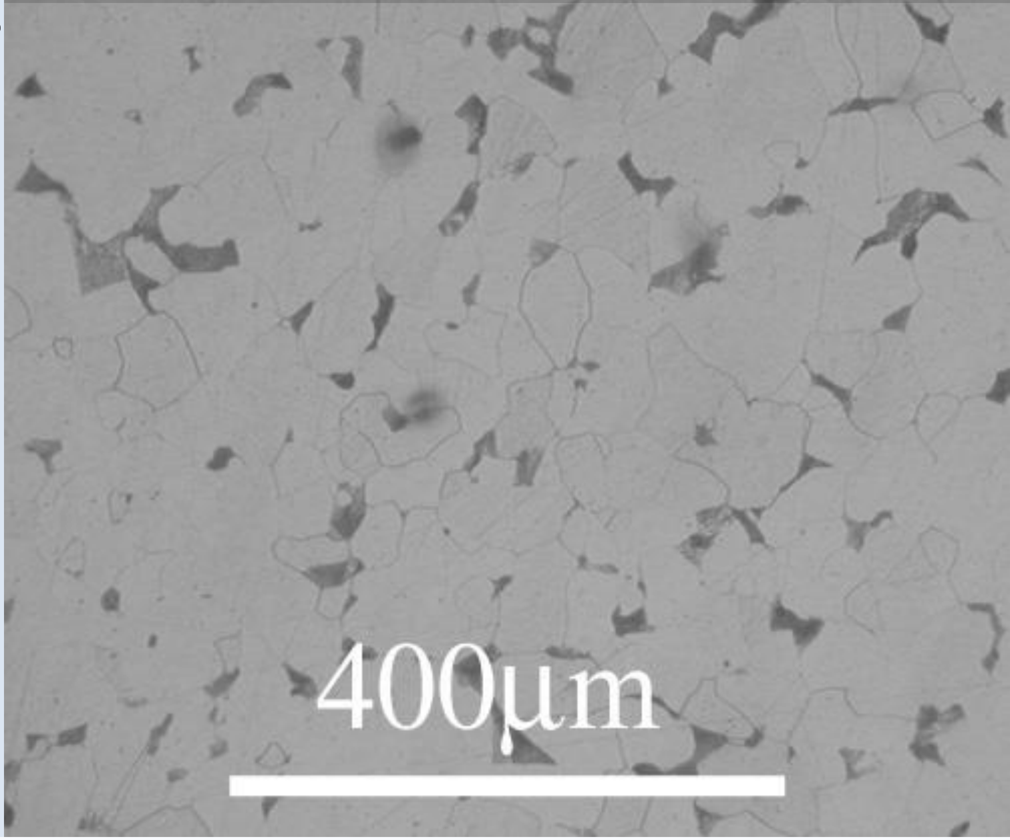
Mild (plain-carbon) and low-carbon steel

**Most common form of steel.
It provides material properties acceptable for many applications.**

It contains approximately
0.05–0.32% carbon
making it malleable & ductile.

**Relatively low tensile strength.
Surface hardness can be increased through carburizing.**

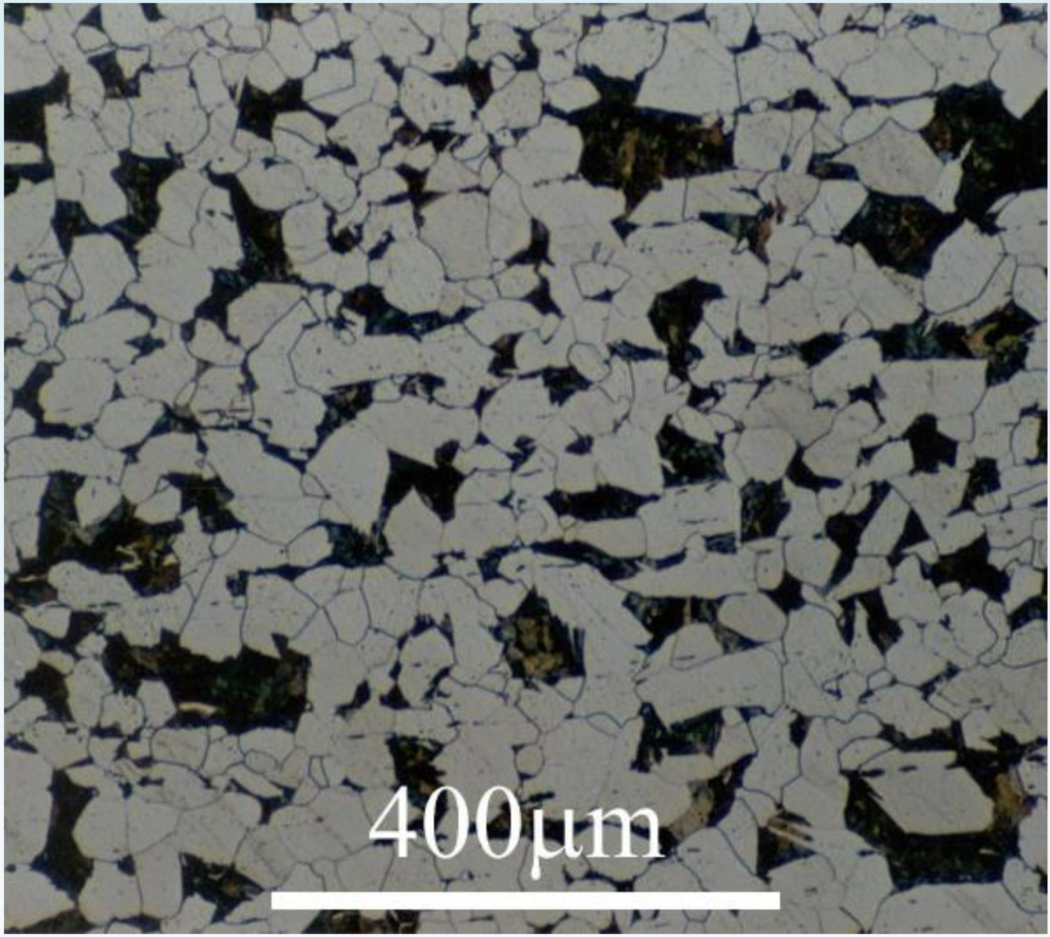
A photomicrograph of 0.1% carbon steel (mild steel). The light areas are ferrite. Note the small amount of pearlite



0.2% Carbon Steel

Increasing the carbon content decreases the amount of ferrite and increases the proportion of pearlite in the structure.

Note the increased amount of pearlite compared with the 0.1% 'dead mild' steel



Focus on Steel – Carbon Steels

A typical application of low carbon steel in a car body.

Higher carbon steels

Carbon steels which can successfully undergo heat-treatment. They have a carbon content in the range of 0.30–1.70% by weight.

Trace impurities of various other elements can have a significant effect on the quality of the resulting steel. Trace amounts of sulfur in particular make the steel red-short, that is, brittle and crumbly at working temperatures.

Manganese is often added to improve the hardenability of low-carbon steels. These additions turn the material into a low-alloy steel by some definitions, (AISI's definition of carbon steel allows up to 1.65% manganese by weight)

Focus on Steel – Carbon Steels

Medium carbon steels

Approximately 0.30–0.59% carbon content.
Balances ductility and strength.
It has good wear resistance;
used for large parts, forging and automotive components

High-carbon steels

Approximately 0.60–0.99% carbon content.
(ASTM 304)
Very strong, used for springs and high-strength wires

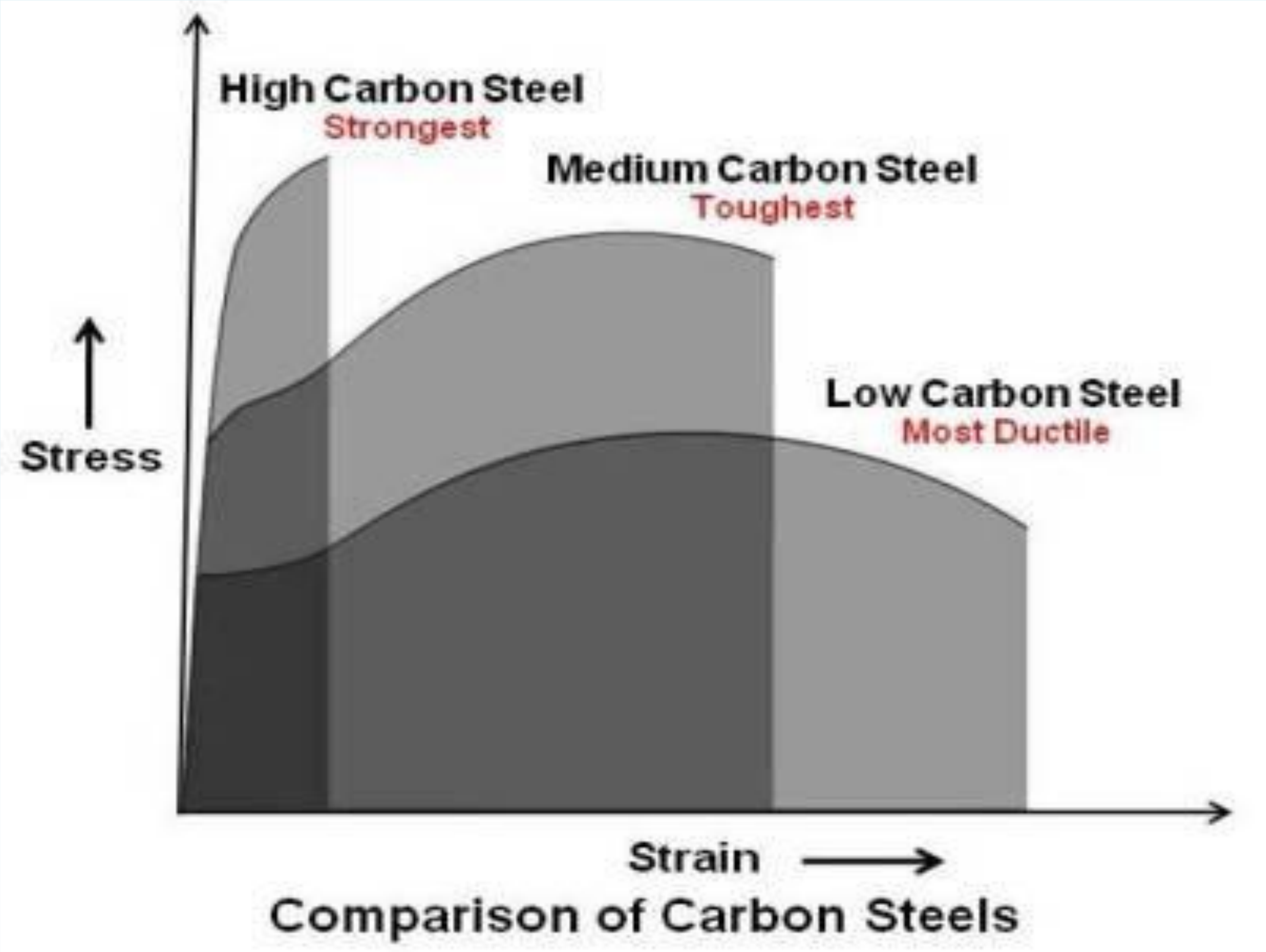
Ultra-High-carbon steels

Approximately 1.00–2.00% carbon content.
Steels that can be tempered to great hardness.
Used for special purposes (knives, axles, punches).
Most steels with more than 1.2% carbon content
are made using powder metallurgy.

Properties of Carbon Steels

Carbon content wt %	Properties	Applications
0.01 - 0.1	Soft, ductile, no useful hardening by heat treatment except by normalizing, but can be work-hardened. Weldable.	Pressings where high formability required
0.1 - 0.25	Strong, ductile, no useful hardening by heat treatment except by normalizing, but can be work-hardened. Weldable. Ductile-brittle transition temperature is just below room temperature	General engineering uses for a mild steel
0.25 - 0.6	Very strong, heat treatable to produce a wide range of properties in quenched and tempered conditions. Difficult to weld. Can become brittle below room temperature.	Bars and forgings for a wide range of engineering components. Connecting rods, springs, hammers, axle shafts requiring strength and toughness.

Focus on Steel – Carbon Steels



Properties of Carbon Steels

Carbon content wt %	Properties	Applications
0.6 - 0.9	Strong, whether heat treated or not. Ductility lower when less carbon is present.	Used where maximum strength rather than toughness is important. Tools, wear resisting components (piano wire and silver steels) are in this group).
0.9 - 2.0	Wear resistant and can be made very hard at expense of toughness and ductility. Cannot be welded. Tend to be brittle if the structure is not carefully controlled	Cutting tools like wood chisels, files, saw blades.

Definition of Mechanical Properties

Mechanical properties of steel are defined as the reaction of the material to certain types of external forces.

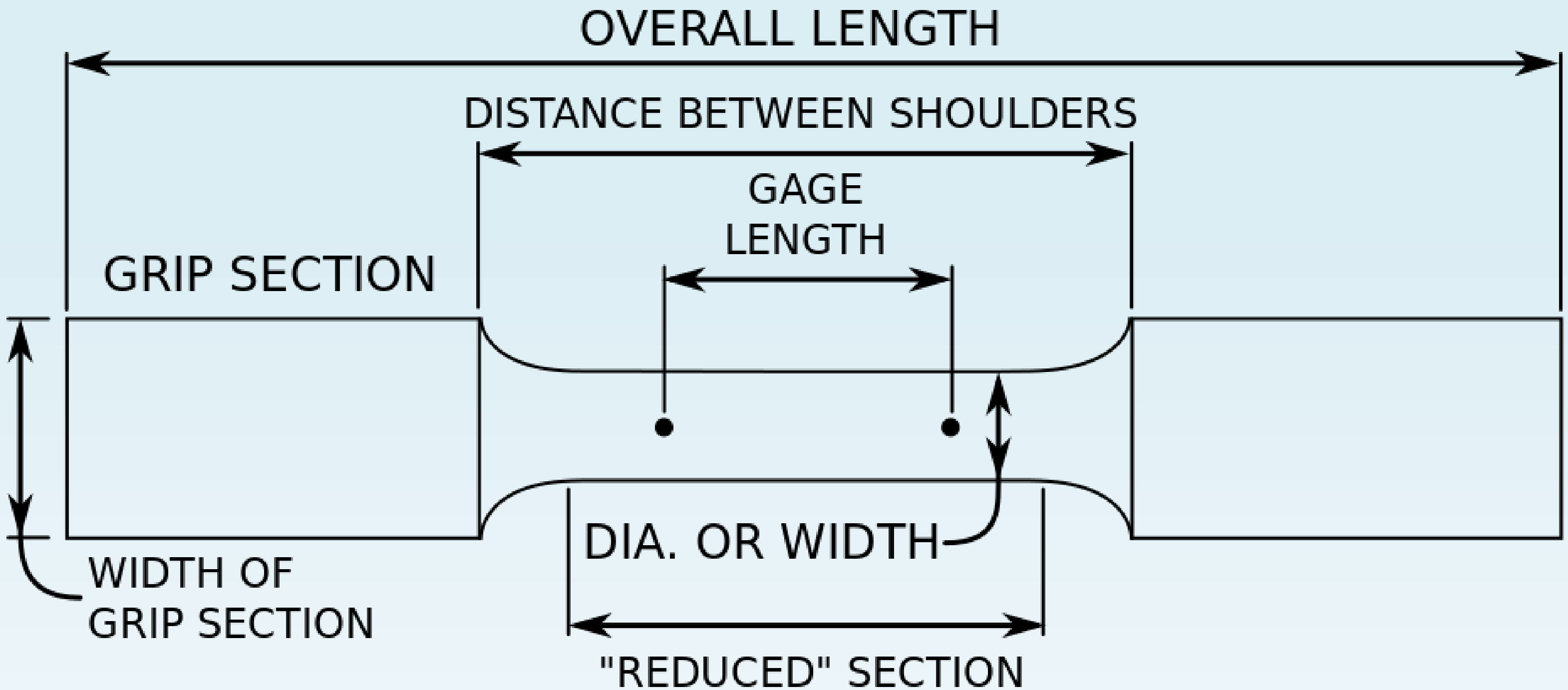
Tensile strength (Ultimate Strength)
The maximum force that a material can withstand before fracturing. This is usually reported in terms of force per unit of area.

Yield strength
The force that a material can withstand before permanent deformation occurs. Also reported as force per unit of area.

Ductility
The ability of a material to deform without fracturing. Generally reported as elongation and reduction of area in a cross section that has been purposely fractured.

Tensile, Yield, and Ductility of steel are determined by performing a Tension Test in which a standard sample of the material is subjected to a pulling force that increases gradually until the material deforms, stretches, and fractures

Tensile Test



Test specimen nomenclature

ASTM E8/E8M-11:

"Standard Test Methods for Tension Testing of Metallic Materials" (2011)

ISO 6892-1:

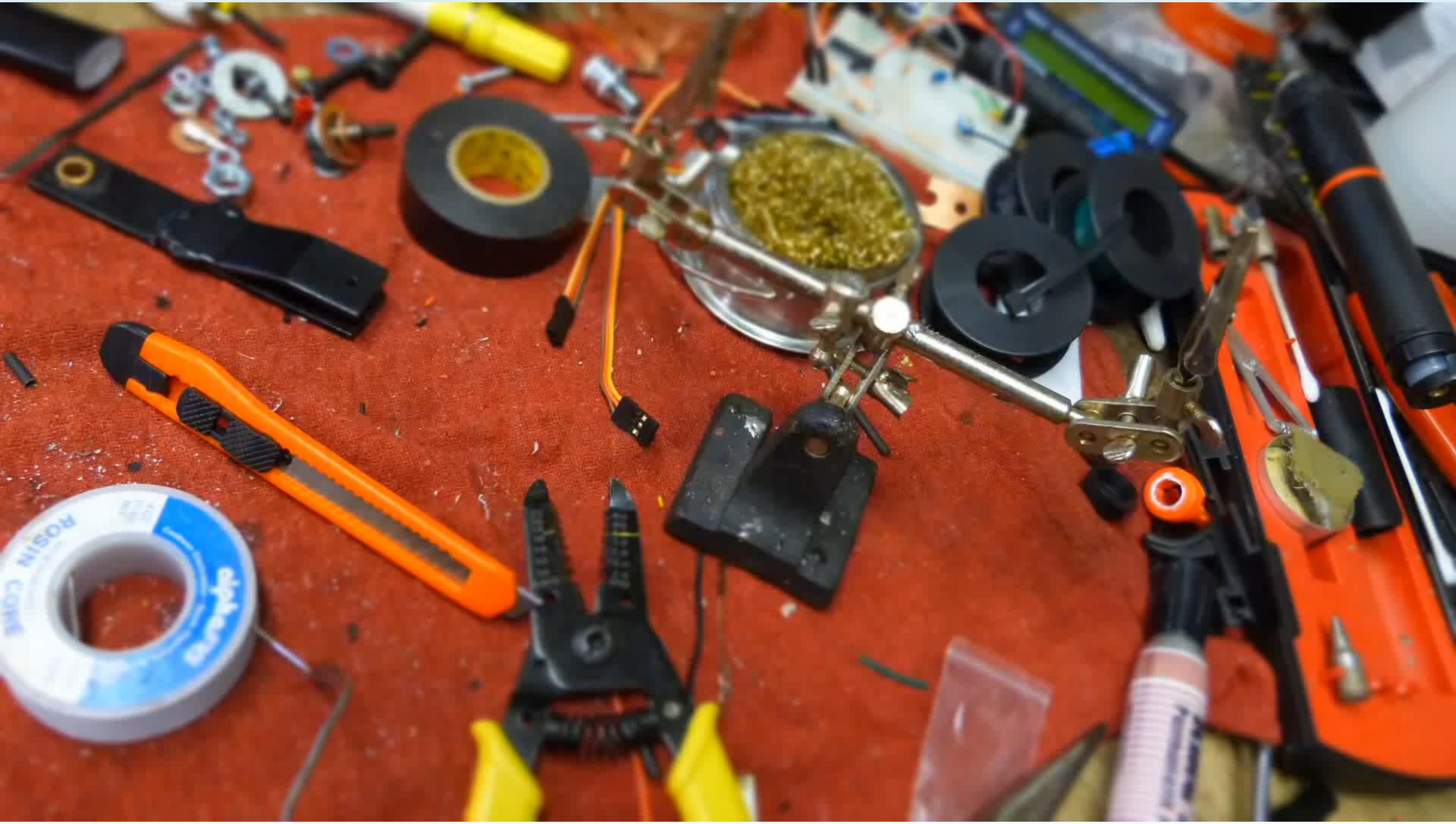
"Metallic materials. Tensile testing. Method of test at ambient temperature" (2009)

ISO 6892-2:

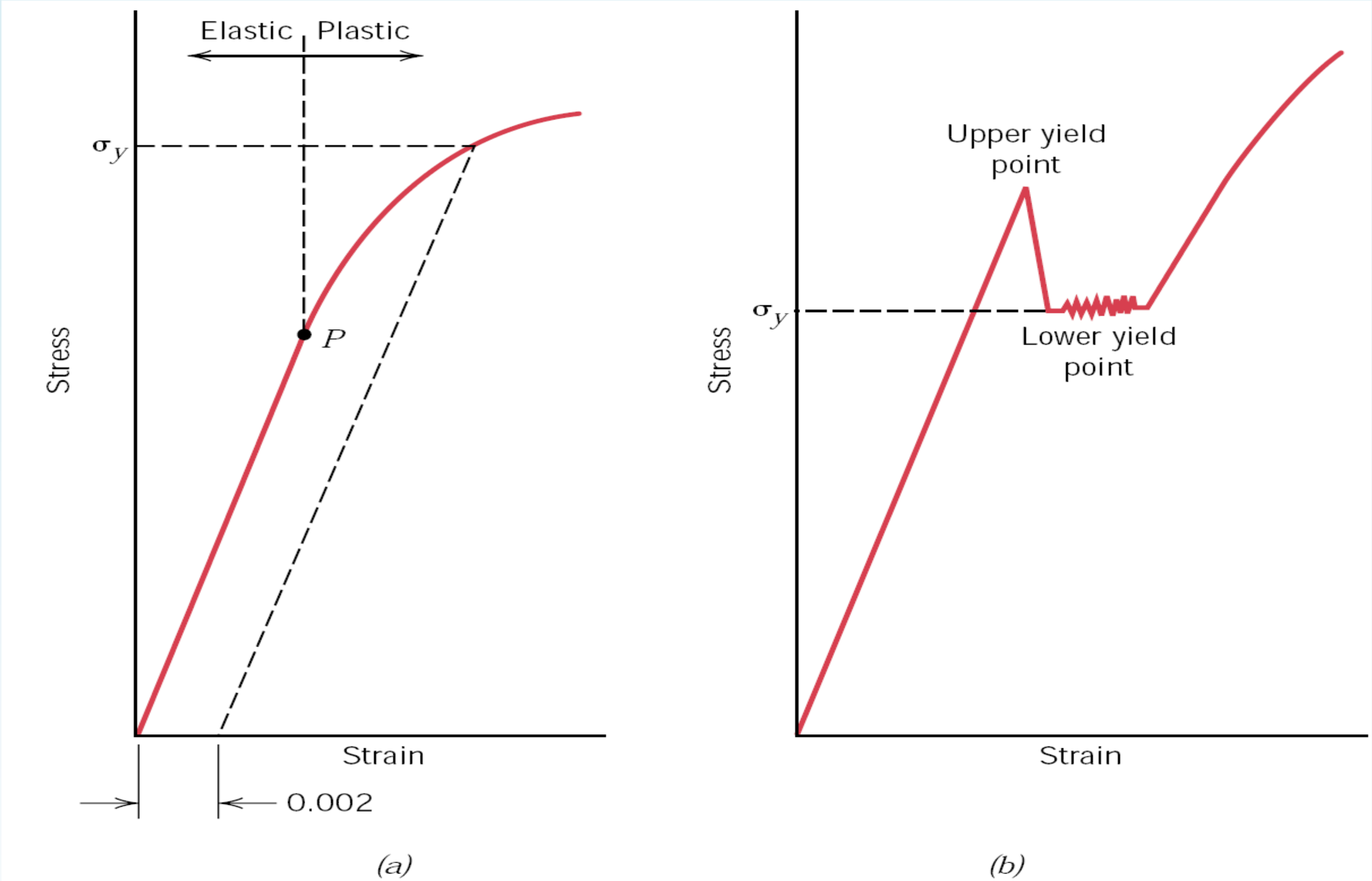
"Metallic materials. Tensile testing. Method of test at elevated temperature" (2011)

Focus on Steel – Carbon Steels

Determination of the elastic limit and the yield strength



Determination of the elastic limit and the yield strength



typical stress-strain curve for a metal.

Stress-strain curve for a material exhibiting the yield point phenomenon

Yield Point Phenomenon

Low-carbon steels exhibit a tensile behavior characterized by the yield point phenomenon. It defines very well the elastic-plastic transition. The yield point phenomenon appears due to a non-homogeneous deformation which begins at a point of stress concentration and propagates through the specimen in form of observable bands, called *Luder's bands*.

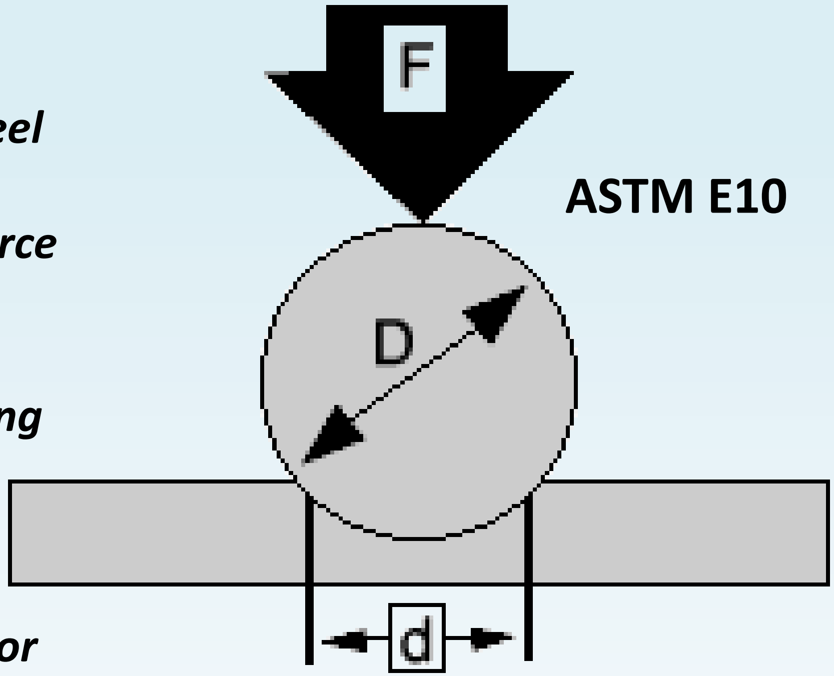
Yielding is initiated at *the upper yield point* followed by an actual decrease in stress. Afterwards, stress fluctuates slightly about some constant stress, termed *the lower yield point*, and subsequently increases with increasing strain


Tensile Test

Definition of Mechanical Properties

Hardness

The resistance of the material to penetration. Not to be confused with hardenability, which is a measure of the ability of a certain steel to respond to heat treatment. Hardness is measured by applying a standard force to the surface of the steel through a small, hardened ball point, and then measuring the diameter of the resulting impression.



Hardness usually is reported as a value on one of two industry standard scales, Brinell or Rockwell. Brinell hardness is usually more accurate for measuring hardness of plate products.

$$\text{HB} = \frac{2F}{\pi D\left(D-\sqrt{(D-d)}\right)}$$

The Brinell number, which normally ranges from HB 50 to HB 750 for metals, will increase as the sample gets harder.

F: Test force 500 – 3000 kgf for 10-15 sec
d: permanent width of indentation
D: Ball indenter diameters (10mm to 1mm)


Brinell
Hardness Test

CHARPY IMPACT TEST
(Charpy V-notch Test)

The Charpy test is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture.

This absorbed energy is a measure of a given material's notch toughness and acts as a tool to study temperature-dependent ductile-brittle transition.

ASTM E23
Standard Test Methods for Notched Bar Impact Testing of Metallic Materials

ISO 148-1 Metallic materials
Charpy pendulum impact test – Part 1: Test method

EN 10045-1
Charpy impact test on metallic materials. Test method (V- and U-notches)

Impact Strength

The ability of a material to withstand a high velocity impact

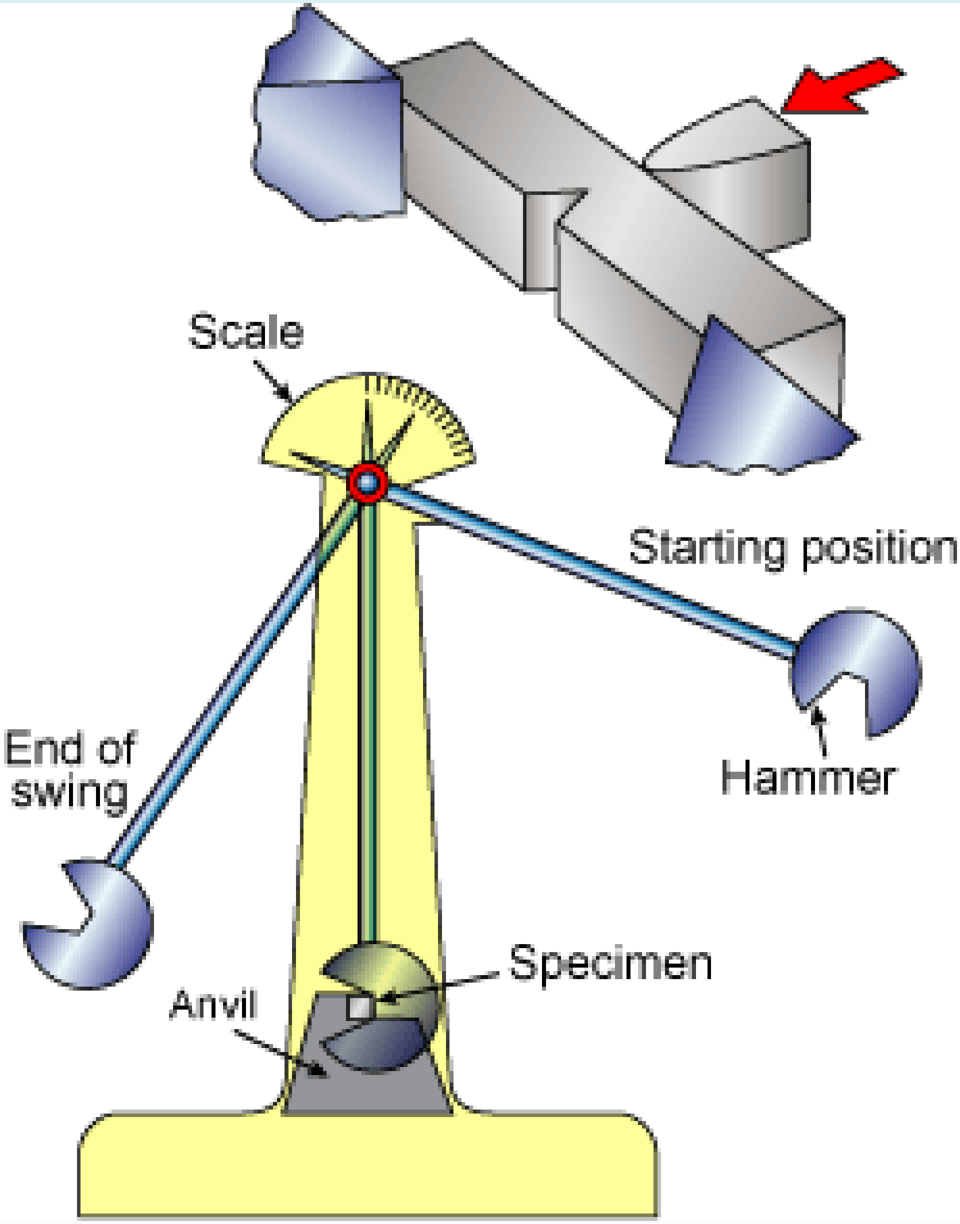
Impact strength is measured by subjecting a standard notched sample to a swinging weight.

The testing requires three standard samples of a defined grain orientation.

The results are reported as joules, showing the average of the three specimen and the lowest value of the three, at the testing temperature.

Impact Strength

The ability of a material to withstand a high velocity impact



Schematic of the Charpy impact test


Charpy Impact Test

Impact Strength

The ability of a material to withstand a high velocity impact

Factors Affecting Charpy Impact Energy
Yield strength and ductility
Notches
Temperature and strain rate
Fracture mechanism

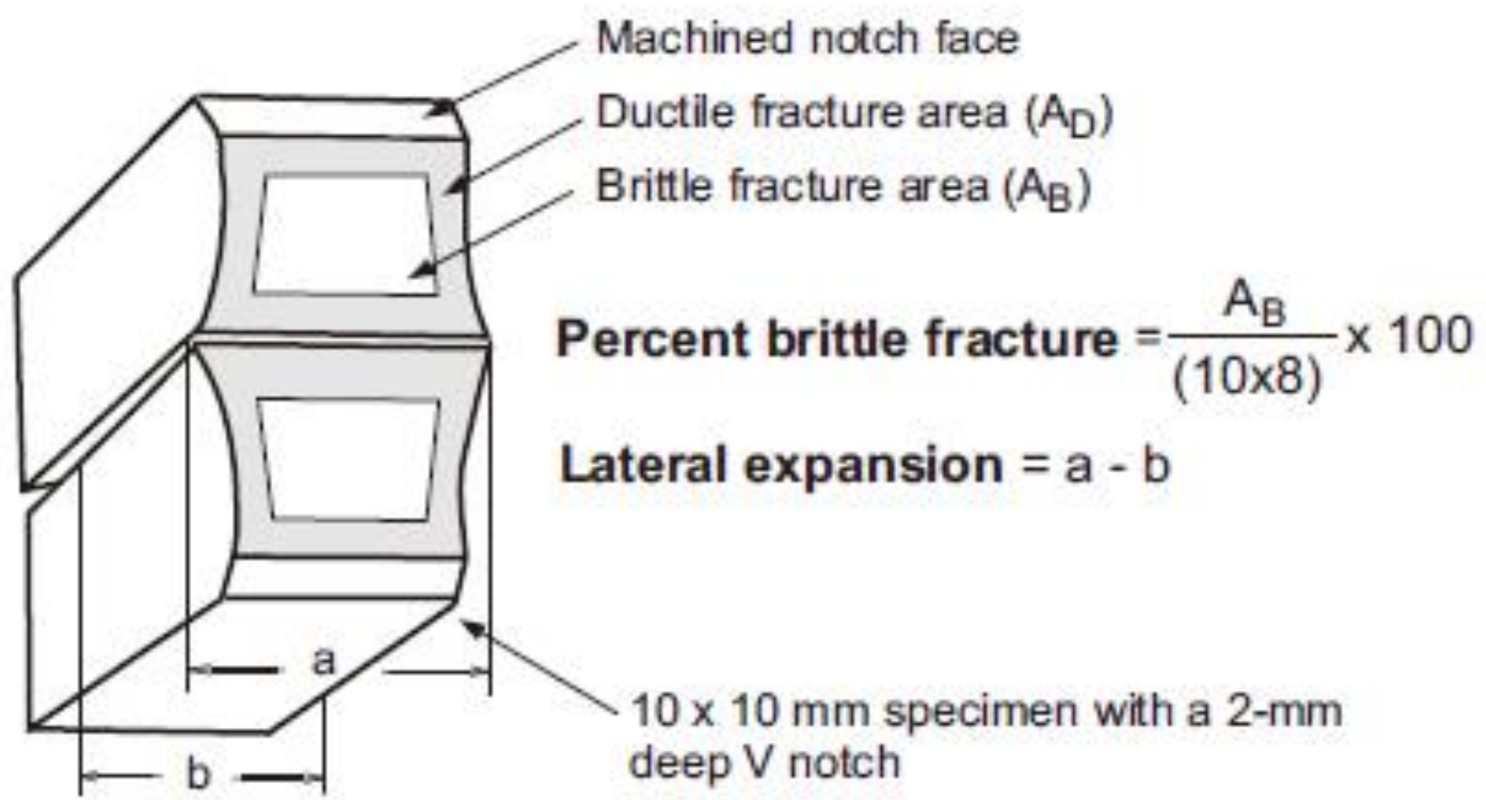
The notch serves as a stress concentration zone and some materials are more sensitive towards notches than others.
The notch depth and tip radius are therefore very important.

Metals fail by one of two **fracture mechanisms**,
micro-void coalescence or cleavage.

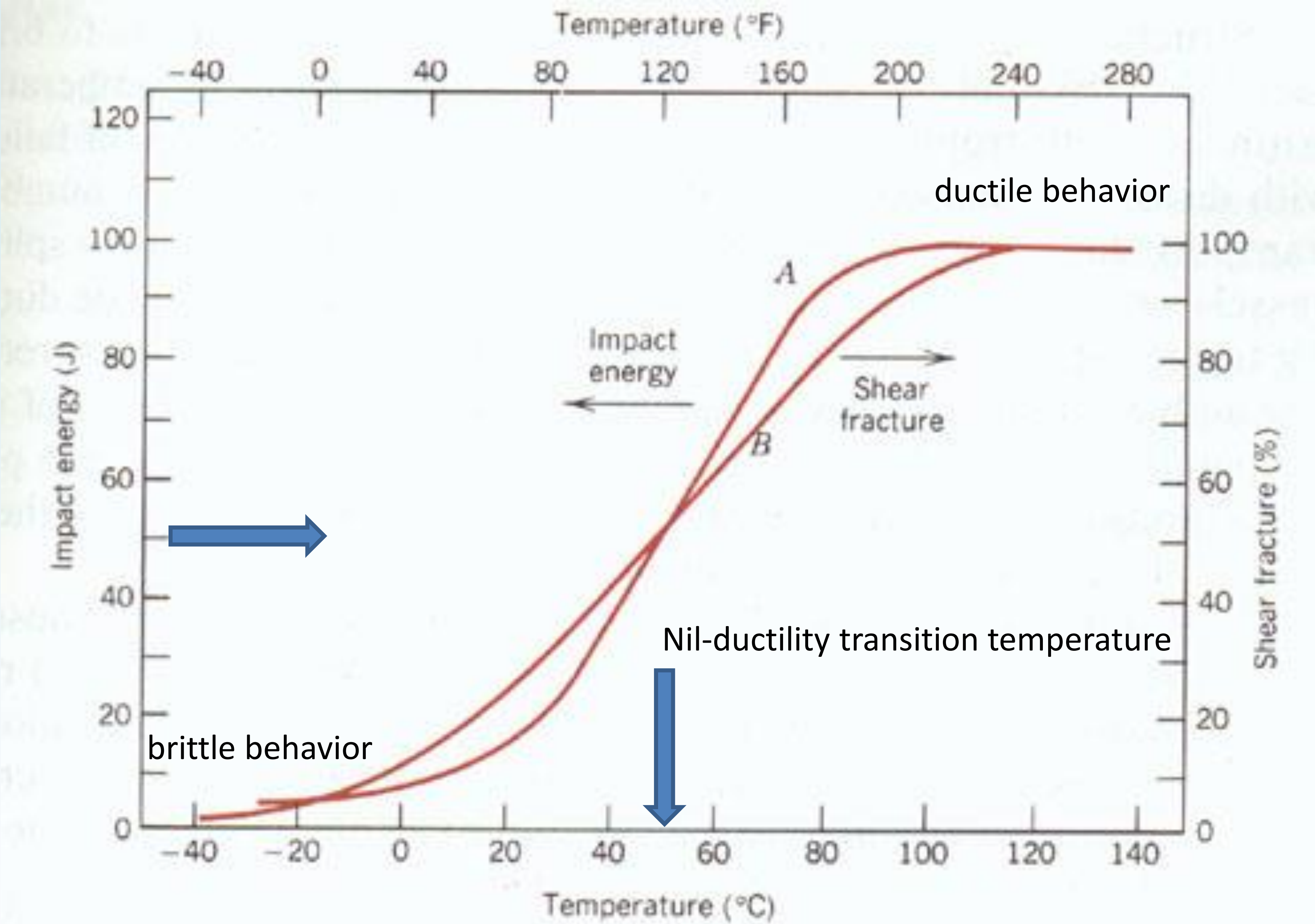
Cleavage can occur in body centered cubic materials,
where cleavage takes place along the {001} crystal plane.

Micro-void coalescence is the more common fracture mechanism
where voids form as strain increases,
and these voids eventually join together and failure occurs.
Cleavage involved far less plastic deformation
ad hence absorbs far less fracture energy.

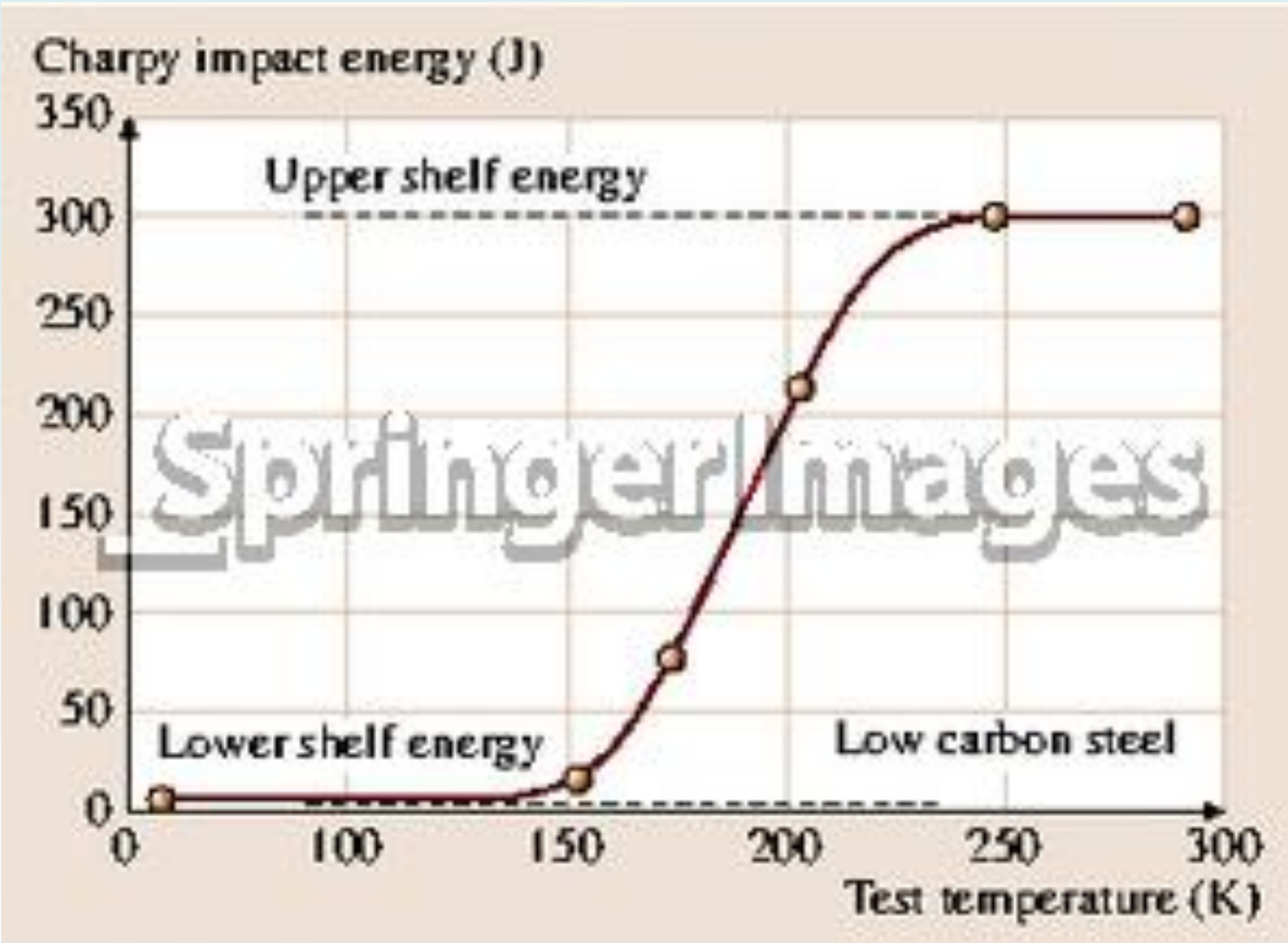
Fracture Mechanisms



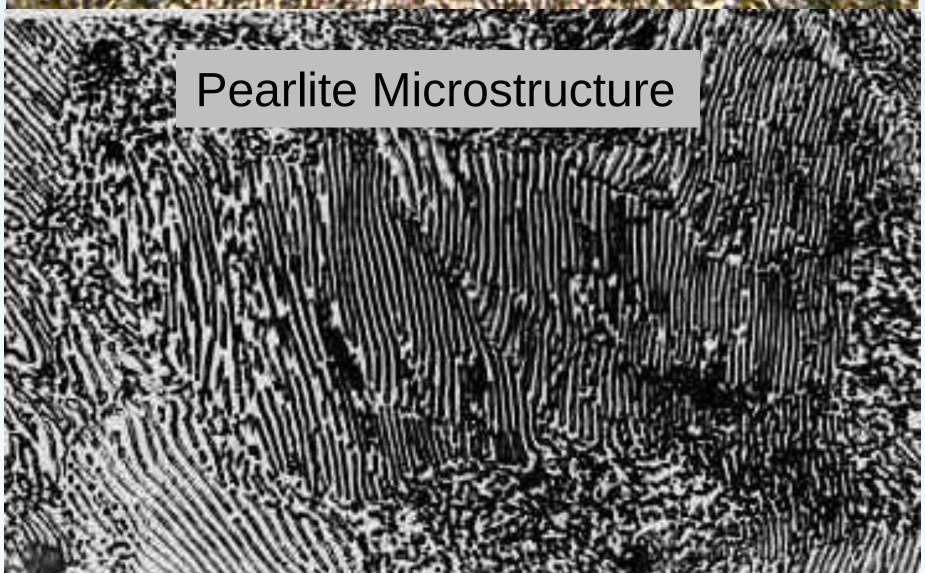
Focus on Steel – Carbon Steels

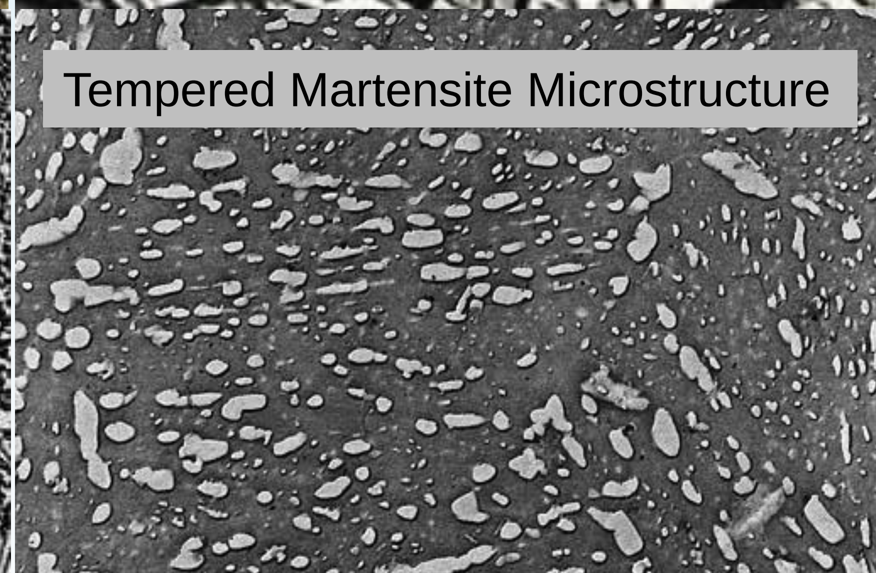


Nil-ductility transition temperature



Focus on Steel – Carbon Steels





Unlimited Range of Properties of Steel

The phenomenon of *Allotropy* in iron
yields the almost unlimited range of properties

through

HEAT TREATMENT

Alloying elements in steel only provides the potential for specific properties.
These properties may not actually be achieved
until processing and heat treatment have been carried out.

Focus on Steel – Carbon Steels

Literature

1. Verhoeven, John D. *Steel Metallurgy for the Non-Metallurgist*. American Society for Metals, (2007), ISBN 9780871708588
2. Maranian, Peter. *Reducing Brittle and Fatigue Failures in Steel Structures*, New York: American Society of Civil Engineers, (2009), ISBN 978-0-7844-1067-7