Content

- Welding Metallurgy
- Phase Transformation
- Heat Treatment of Steel
- Types of Steel for Welded Structure
- Types of Mill Certificates
- HAZ and Toughness of Steel
- Weldability and Weld Defects

No of Slides – 54
Estimated Duration – 1 Hour

Welding Metallurgy

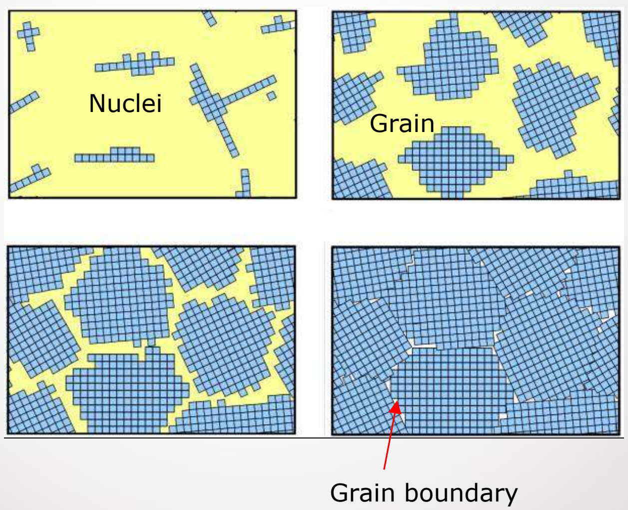
Welding Metallurgy differs from Conventional Metallurgy in certain important aspects.

- Physical Metallurgy
  - Study of structure of metals and their properties
  - Extraction → Refining → Preparation for use
  - Preparation (Alloying, Rolling, Heat treating and so on)
  - The Field is so abroad, no means exhaustive

- Welding Metallurgy Phenomena (Complex Metallurgy Process)
  - Melting
  - Freezing
  - Diffusion (The movement of individual atoms)
  - Precipitation (The formation of a new solid phase within a solid metal or alloy)
  - Solid state transformation
  - Thermal strain
  - Shrinkage stress

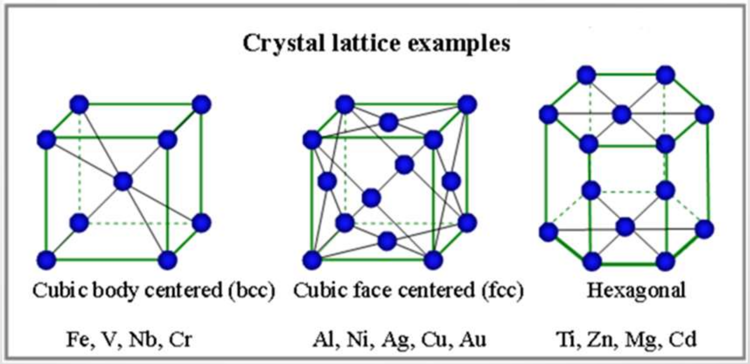
Solidification

- The atoms composing liquid metals have no orderly arrangement - Amorphous
- Liquid metal approach solidification temp. when weld metal cool down
- Solid particles known as Nuclei beginning to form
- The individual nuclei grow into larger – called Grains
- Each grains grow independently
- Crystalline Structure/Lattice orientation of grain differ from one grain to another
- Orderly arrangement of atoms is disrupted where grains meets (Grain boundary)



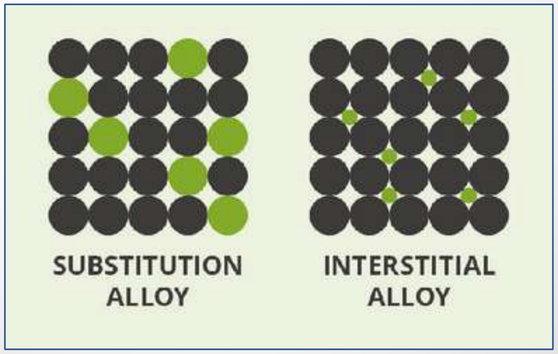
Grains and Properties of Metal

- Each grain in pure metal has same crystalline structure at given temp. (same atomic spacing)
- Mechanical properties depended on size and orientation of the grains
- At grain boundaries
  - Spaces between atoms larger than normal
  - Many vacancies and missing atoms
  - Permit atoms to move with relative ease (Diffusion)
  - Odd sized atoms segregate and formation of undesirable phases
  - Increase susceptibility to cracking during welding and heat treatment
  - Reduce corrosion resistance



Alloying / Solid Solution

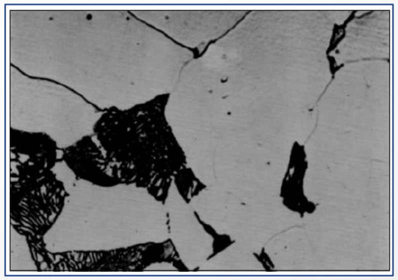
- Properties of metallic element can be altered by addition of other elements
  - Carbon added to iron to form the alloy steel
  - Zinc added to metal copper to form brass
- Substitutional alloying – alloying atom (solute) replace one of base metal atoms (solvents) in the lattice structure
  - Gold dissolves in Silver
  - Copper dissolve in Nickle
- Interstitial alloying – alloying atoms (solutes) small enough to dissolve in the space between parent metal atoms (solvents) without occupying lattice sites
  - Carbon, hydrogen, oxygen, nitrogen and boron can alloy interstitially in iron



Multiphase Alloys

- Alloying atoms do not dissolve completely, either substitutionally or interstitially
- Formation of mix atomic groping (Different Crystalline Structure) – Different Phase
- Individual Phase can be distinguished by conducting metallography

- Metallography
  - Polishing
  - Etching
  - Examination at 50X to 2000X



Typical microstructure of two-phase alloy

Steel : Fe + C (<2%)

- Carbon
  - Low carbon steel ~0.3%
  - Middle carbon steel 0.3~0.5%
  - High carbon steel 0.5%~
- Alloy components

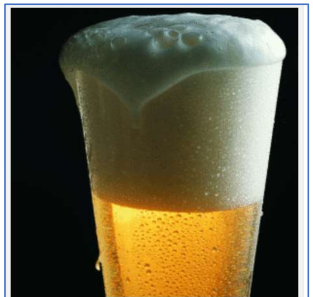
  Mn, Si, Ni, Cr, Cu, Mo, Nb, V, Al, Ti, and B
  - High alloy 10%~
  - Middle alloy 5~10%
  - Low alloy ~5%

  Mn, Si :for welding (de-oxidization)

  Mn, Si, Al :from refining process
  - Rimmed steel
  - Semi-killed steel
  - Killed steel (de-oxidized with Si,Al)
- Impurities

  S, and P -> Lamellar tear, hot crack

As carbon content increases, strength generally increases but elongation, toughness and weldability deteriorate.



Because gas is still evolving, this beer is NOT KILLED.

In steel making the main reaction is the combination of Carbon in the melt with Oxygen to form a gas, CO and CO2.
to control the evolution of gas, chemicals called **deoxidizers** are added to the steel.
If sufficient deoxidizers are added, no gas is evolved from the solidifying steel, and the steel is said to be “killed.”

Phase Transformation

- Phase Transformation
  - Metallurgical/Phase transformations occur in a metal when heated from room temp to higher temp and cooled from higher temp to lower temp during welding
  - The effect of metallurgical transformations on the metal properties mainly depend on cooling rate and chemical composition

- Mechanical properties of a metal
  - Strength – Ability withstand the applied load
  - Hardness – Ability to resist indentation by harder object
  - Ductility – Ability to deform/stress without failing
  - Toughness – Ability to absorb energy
  - Fatigue Strength – Resistant to failure under repeated/cyclic loads
  - Abrasive – Resistance to wear by friction

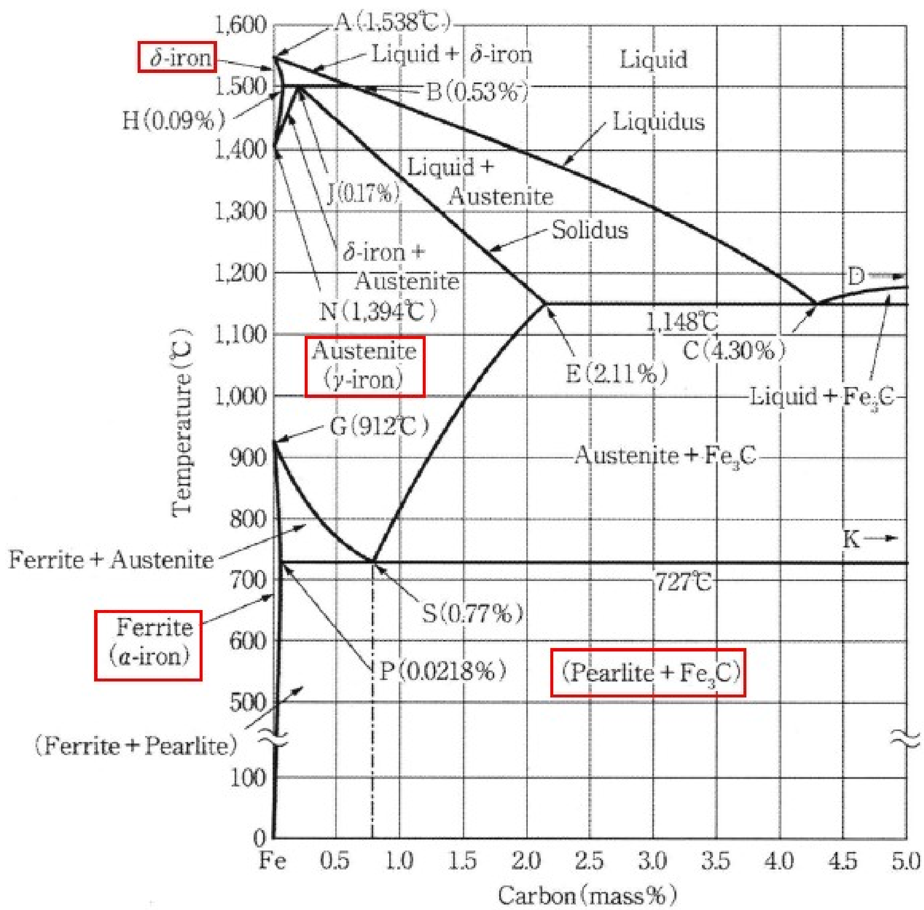


Fig. 2.1.1 Fe-C equilibrium phase diagram [1)]

- Phase diagrams are made under equilibrium condition
- Samples are heated and cooled at very slow rates, allowing time for atom to diffuse and energy barriers to be overcome
- Required for changing one phase to another.

- Approx. description of commercial alloy
- Critical Temp.
- Melting Points
- Microstructure
- Solubility
- Solidification
- Phase Changes

Critical Temperature

- *Temperature at which one phase is changed to another phase*

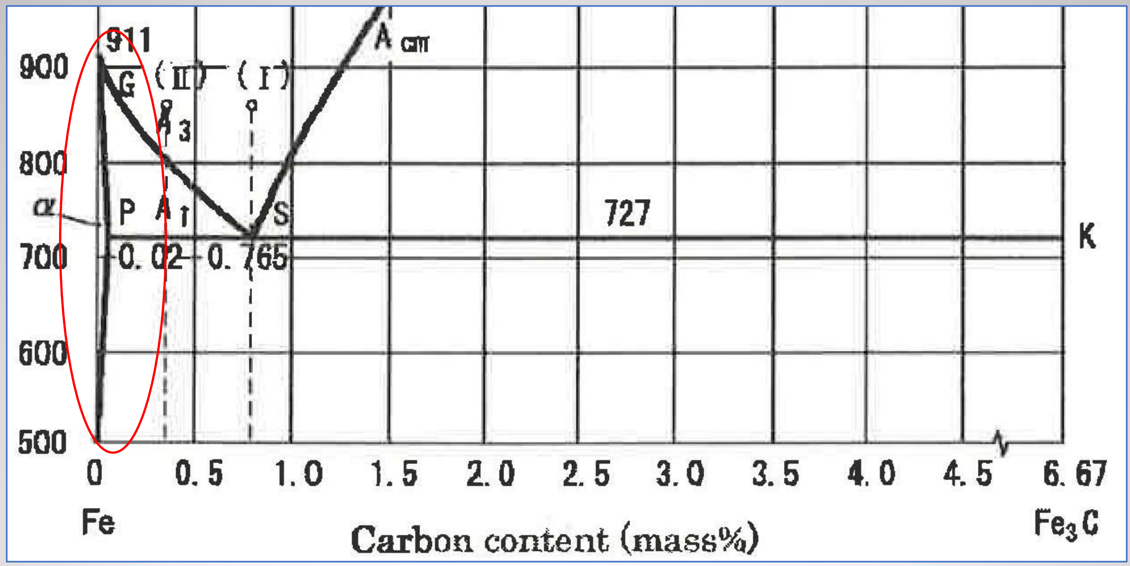
Equilibrium

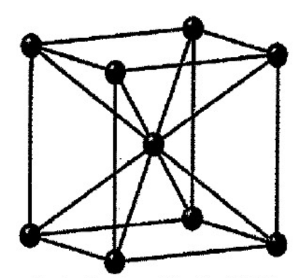
- *Condition of chemical, physical, thermal and mechanical or atomic balance*

Commercial alloys

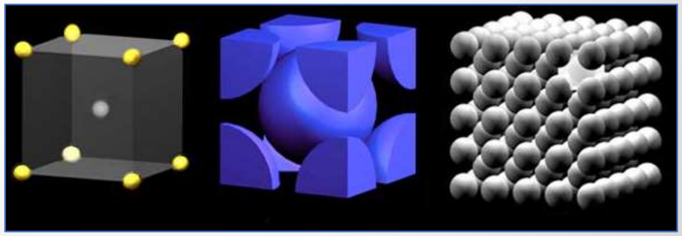
- *Have more than two components, complex and difficult to interpret*

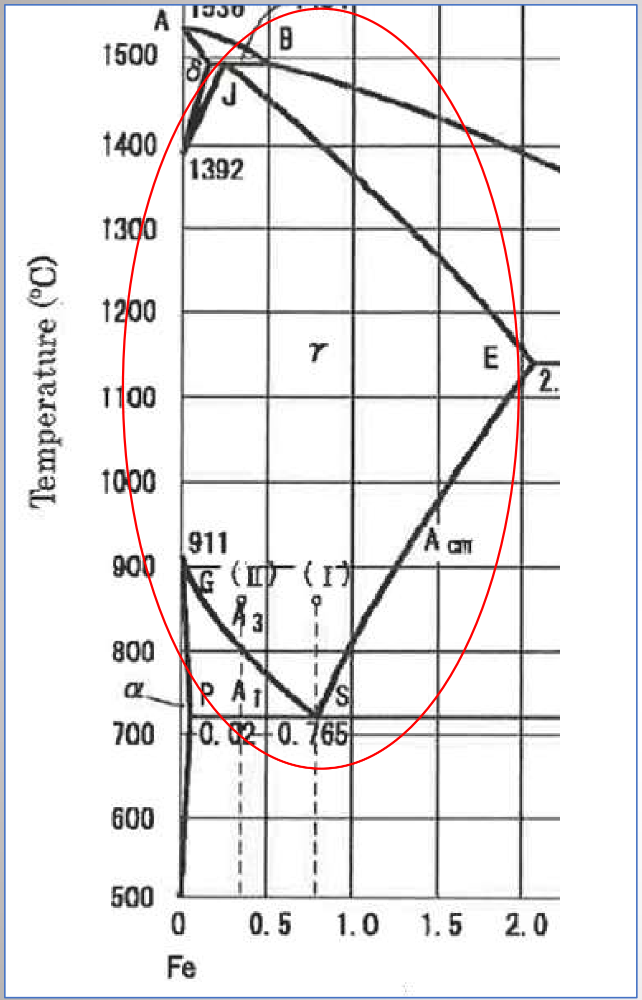
Mass is the same regardless of places.
Weight changes place to place.

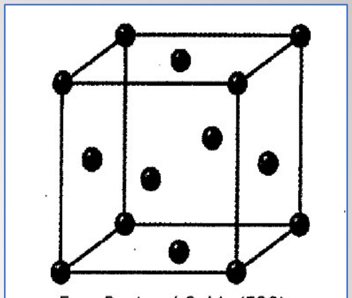




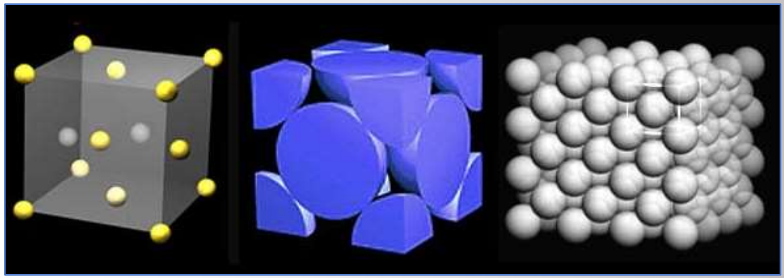
Body Centered Cubic (BCC)

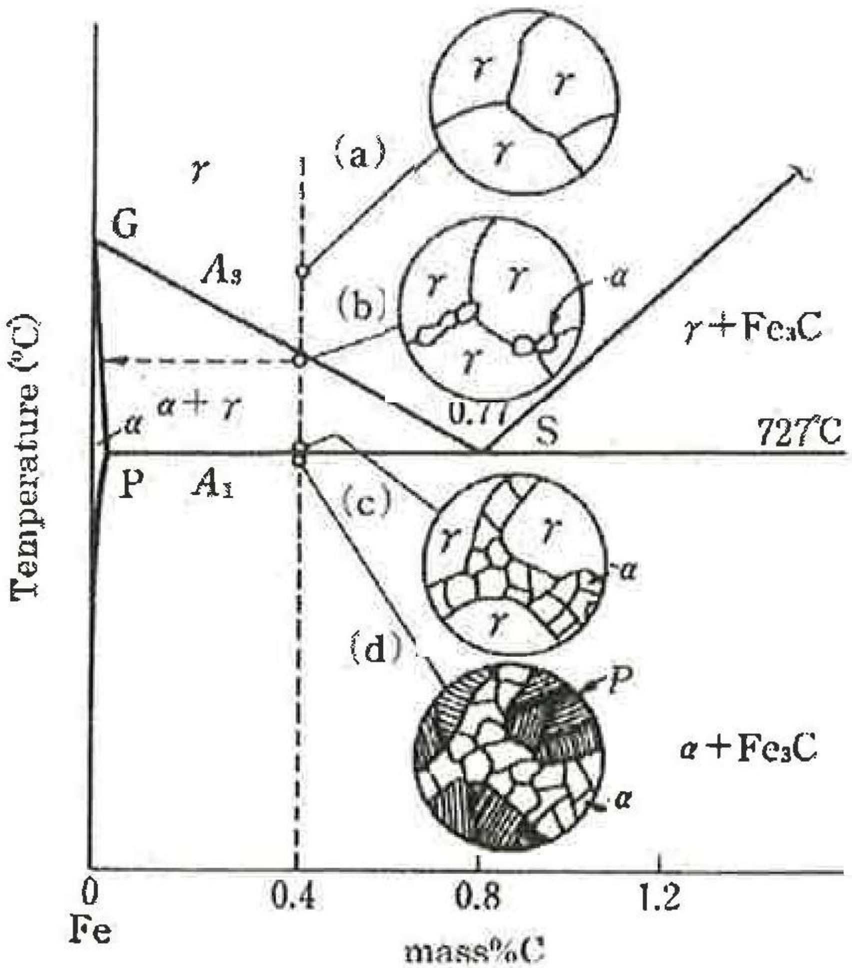






Face Centered Cubic (FCC)





(a) Austenite

(b) Nucleation of ferrite in austenitic grain boundary

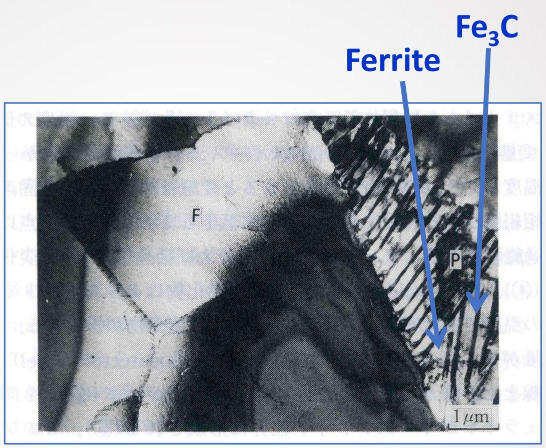
(c) Growth of ferrite in grain boundary

(d) Pearlite transformation from austenitic grain

Fig. 2.2 Change in microstructure of a slowly cooled 0.4%C steel

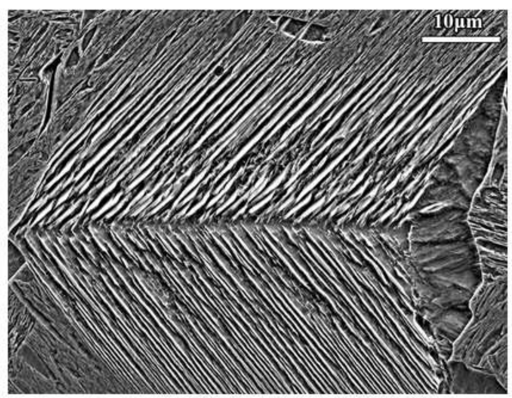
Pearlite

- Steel heated to austenitic range and cooled slowly – resulting microstructure contain pearlite – soft and ductile
- Pearlite – a mixture of cementite (Fe3C) and ferrite that forms in plate or lamellae



Bainite (Zw)

- At faster cooling rate, Bainite formed
- Feathery arrangement of shear needles fine carbides in ferrite matrix
- Higher strength and hardness but lower toughness than pearlite
- The temperature range for transformation of austenite to bainite (125–550 °C) is between those for pearlite and martensite



Bainite microstructure

Martensite

(Hardest austenite decomposition product)

- Very rapid (very fast) cooling or quenching – carbon become trapped in the lattice due to the atoms do not have time to move around – form Martensite characteristically high in hardness and tensile strength, low in ductility and toughness

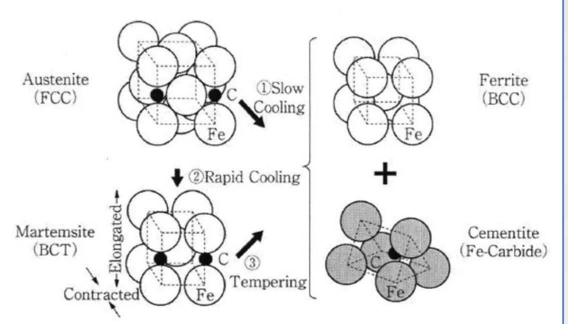


Fig. 2.1.2 Transformation of steel and its crystal structure [2)]

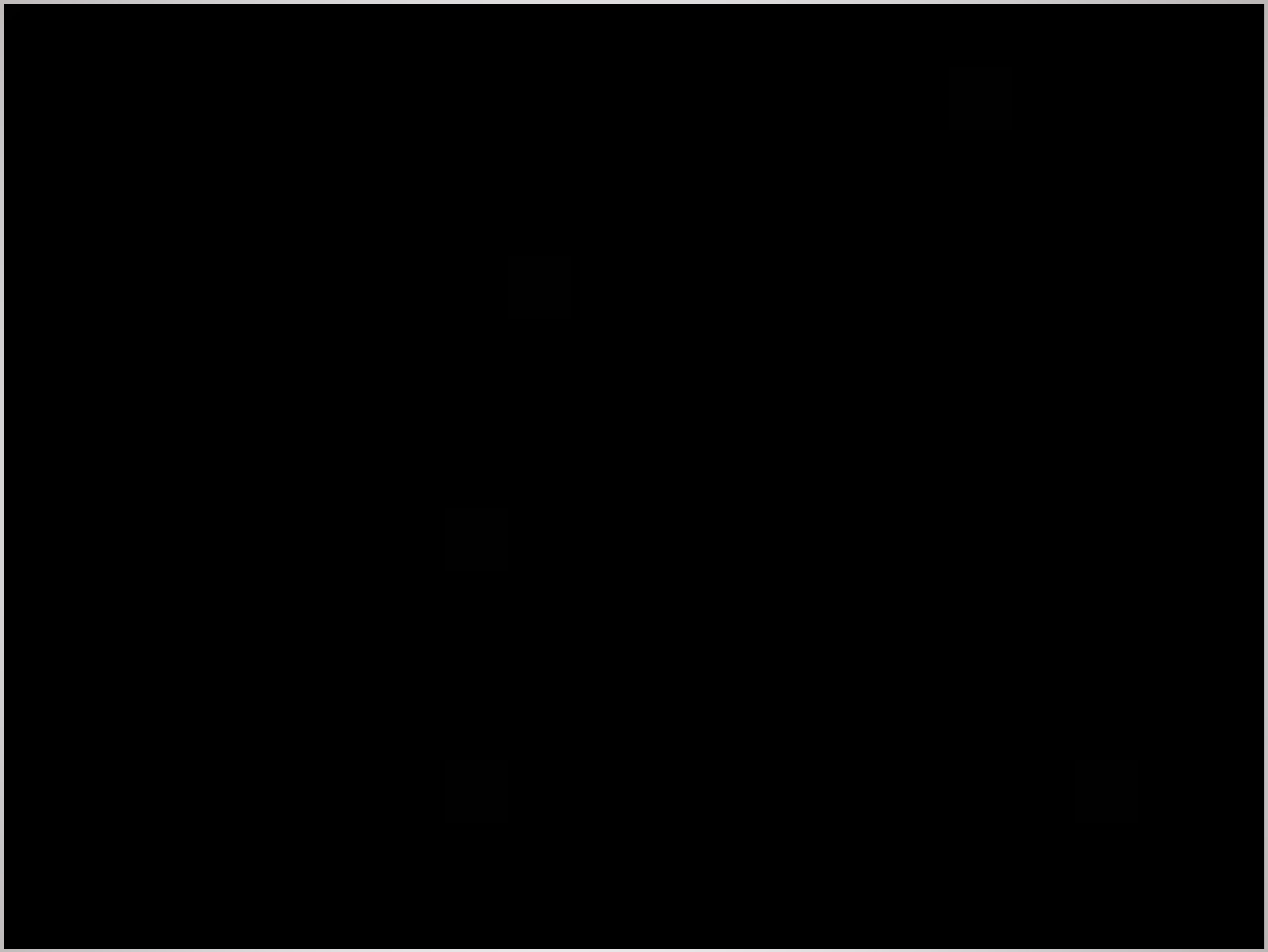
Hardenability

- *Describing the transformation of austenite*
- *Measure of amount of Matensite that forms in microstructure upon cooling*

Hardness

- Function of the carbon content of the steel

Atomic of Steel



Heat Treatment

- Steel properties (both Mechanical and Physical) are changed significantly
- Consideration
  - Chemical composition
  - Shape
  - Thickness of the material
  - Temperature
  - Holding / Soaking Time
  - Cooling rate

Strain Hardening

- *Metals plastically deformed at room temp. (e.g cold rolled or forged)*
- *Number of changes take place in their microstructure*
- *Each individual grain much change shape to achieve the overall deformation*
- *As deformation proceeds, each grain become stronger, making it difficult to deform further*

Strain Aging

- Strain aging is a time-dependent phenomenon in metals, particularly steel, where mechanical properties change after plastic deformation.
- It involves the diffusion of interstitial atoms (like carbon or nitrogen) to dislocations, increasing the material's yield strength and reducing ductility.

Cold Working

- *Plastic deformation of metal with the intent to change its shape and improve mechanical properties at low temp.*

Types of Heat Treatment

- **Annealing** – Softening treatment to increase ductility at the expense of its strength (raised into austenitic range 30~50 C higher, soaked to make homogeneous austenitic structure, then gradually cooled in furnace to room temp) - *Recrystallization to induce softening and homogenize grains*

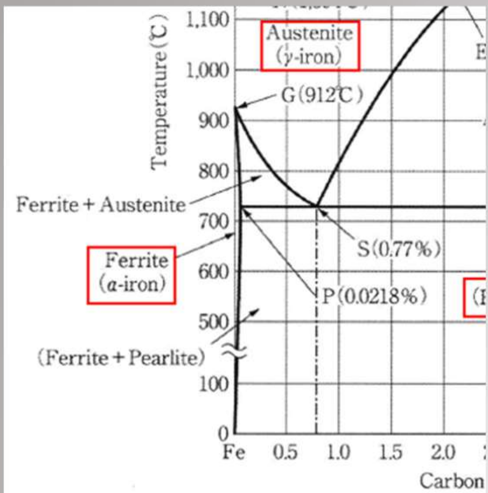
- **Normalizing / Homogenizing** – Softens the metal to get homogeneous austenitic structure (raised into austenitic range 50 C higher, held for short time, then slow cool in still air) - *Grain refinement and remove internal residual stress*

- **Quenching** (Oil / Water / Brine) – Increased hardness and strength & decreased ductility (Heated to a temperature about 50C higher than Ac3 to make it fully austenitized, followed by rapid cooling by immersing in salt water, water or oil to produce martensite)

- **Tempering** – Normally follow quenching process to improve ductility (reheat to below lower transformation temp, 50C lower than Ac1, held for short time, then cooled – stressed martensite structure to relax)- *This heat treatment allows carbon to precipitate in the form of tiny carbide particles. The resulting microstructure is tempered martensite which compromise between strength and toughness by choosing proper tempering temp. and time.*

- **Thermal stress relieving / Post-Weld Heat Treatment** – Thermal/residual stresses created by welding heat to relax and metal to recover (reheat weld and base metal to below lower transformation temp gradually and uniformly, held for stress relief, then cool at a moderate rate – to eliminate problems associated with distortion) *- held for one hr. per inch for up to 2 inches thickness.*

(The rates at which Austenite cooled to room temp.)



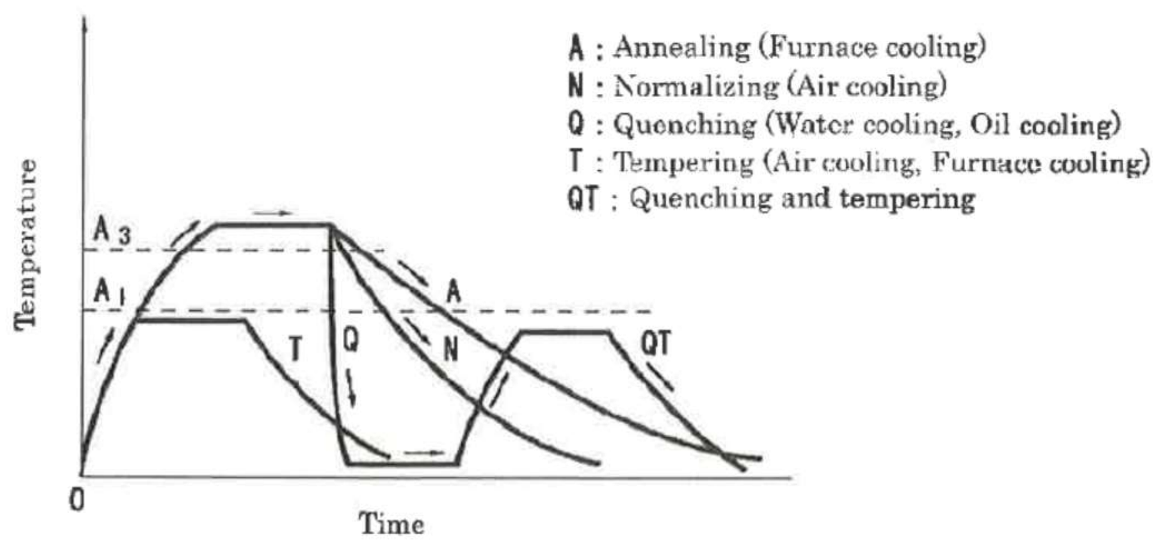
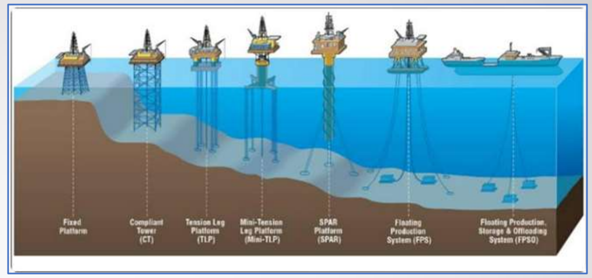


Fig. 2.3 Types of heat treatment of steel

Steel for Welded Structure

- Used in all fields in the form of shape, plate, bars and pipes
  - Ships
  - Offshore Structures
  - Vessels
  - Bridges
  - Vehicles
  - Buildings



Type of steel for welded structure

1) Low Carbon steel
   - General steel structure - SS
   - Welded structure marine - SM
   - Building new earthquake design - SN
2) High Strength Steel – QT / TMCP
3) Low Temp. Service steel - SLA
4) High Temp. Service steel boiler – SB
5) Atmospheric Corrosion Resistance steel - SMA

Tensile Test

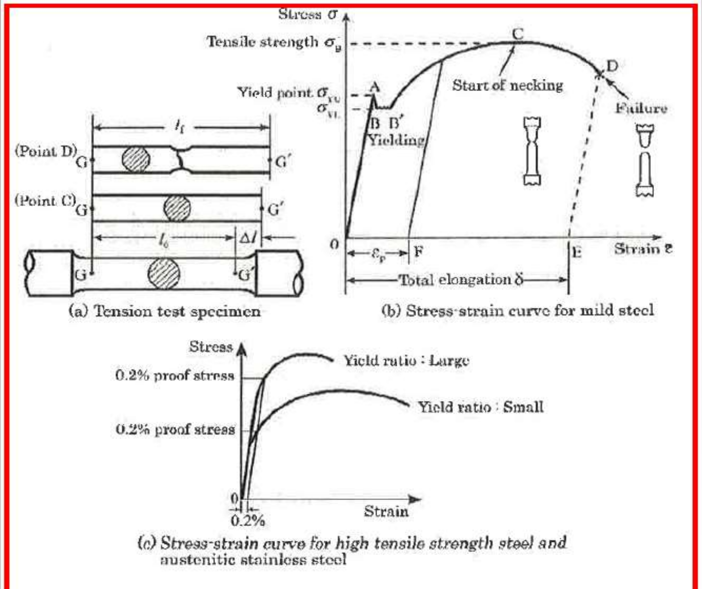
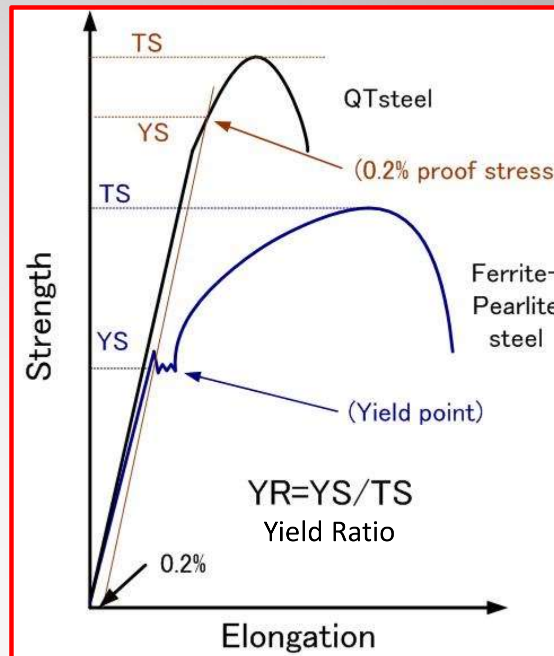


Fig. 3.12 Stress-strain curve obtained by tension test

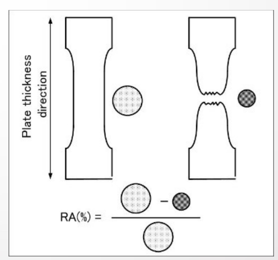


Total Elongation

$$\delta = \frac{l_f - l_0}{l_0} \times 100 \quad (\%)$$

Reduction of Area (RA)

$$\phi = \frac{A_0 - A_f}{A_0} \times 100 \quad (\%)$$



Charpy Impact Test

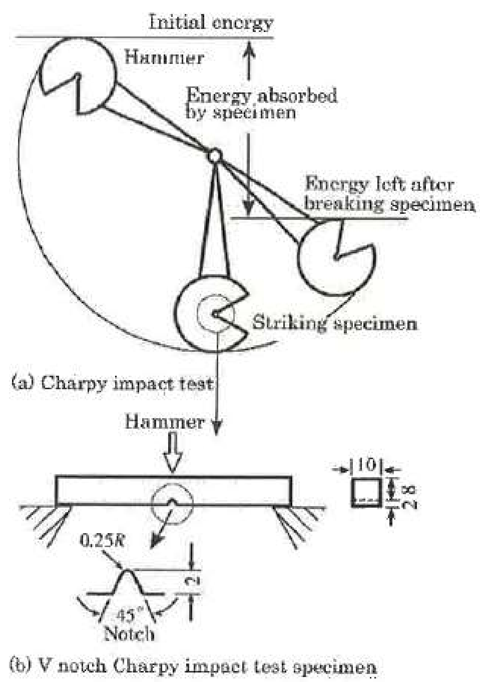


Fig. 3.17 Charpy impact test

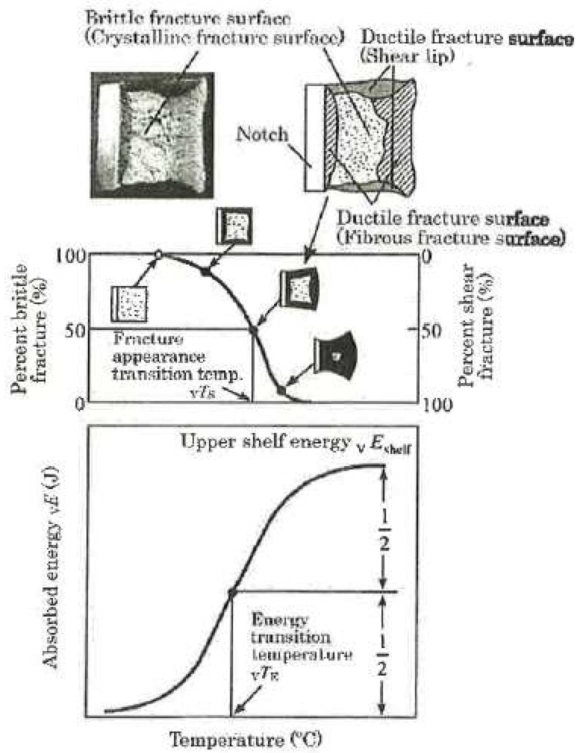
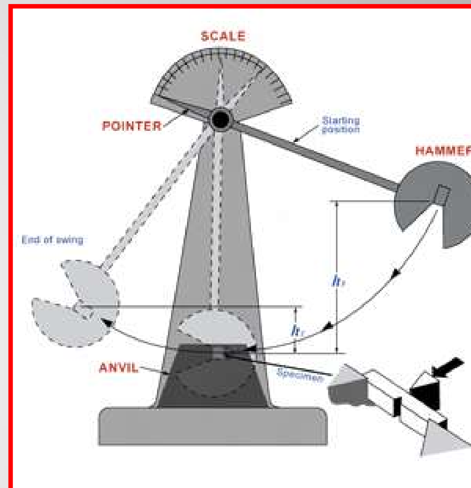


Fig. 3.18 Transition temperatures obtained by V-notch Charpy impact test



1) Low Carbon Steel (Mild Steel)

(Carbon content of 0.3mass% or less)

- **SS (General Steel Structure)**
  - No spec. in Charpy Absorb Energy
  - No spec. for C, Mn, Si
  - Content of only P and S are specified
  - May generate weld cracking and poor in tough
  - Not adequate for significant or large welded structure
  - TS 400 ~ 510 N/mm2
- **SM (Steel Marine)**
  - Design for Welded Structure
  - Designation A, B and C indicates requirement and level of Toughness
  - Suitable for large welded structure
  - TS 400 ~ 720 N/mm2
- **SN (Steel for New Structure/Design)**
  - Specified CE (Carbon Equivalent), Pcm (Cracking susceptibility index) and Yield ratio
  - Specified reduction area in thickness direction (Grade C)
  - Low S content (comparing with SM steel)
  - Have mechanical properties and weldability satisfy earthquake design
  - Two level of TS 400 and 490 N/mm2

JIS standard and steels

- Steels for
  - General structure — SS series (SS400, SS490, etc...)
  - Weld structure — SM series
  - Building construction — SN series (Tensile strength)

Table 2.1 Extract from JIS requirement for rolled steel (mild steel)

		Rolled steels for general structure JIS Z 3101:2004	Rolled steels for welded structure JIS Z 3101:2004		
		SS400	SM400A	SM400B	SM400C
Plate thickness (mm)		16 – 40	16 – 50		
Chemical composition (%)	C_{max}	–	0.23	0.20	0.18
	Mn	–	≧2.5C	0.60 – 1.20	≦1.40
	Si	–	–	≦0.35	≦0.35
	P_{max}	0.050	0.040	0.040	0.040
	S_{max}	0.050	0.040	0.040	0.040
Tensile properties	Yield point (N/mm^2)	≧235	≧235 (16 –40 mm)		
	Tensile strength (N/mm^2)	400 – 510	400 – 510		
	Elongation (%)	≧21	≧22 (16 – 50 mm)		
V-notch Charpy impact value (J)		–	–	≧27 (0°C)	≧47 (0°C)

- Steels for
  - Weld structure

SM series

Table 2.2 Rolled steel for welded structures (Extracted from JIS G 3106:2004)

Class	Symbol		Chemical composition (Max.%) C ≦50 mm	C >50 mm	Si	Mn	Tensile strength (N/mm^2)	Lower limit of yield point (N/mm^2) ≦16 mm	16–40 mm	>40 mm	V-notch Charpy impact value Temp (℃)	Avg (J)
Class 1	SM400	A B C	0.23 0.20 0.18	0.25 0.22 –	– 0.35 0.35	2.5[C] 0.6–1.20 1.40	400 – 510	245	235	215	– 0 0	– 27 47
Class 2	SM490	A B C	0.20 0.18 0.18	0.22 0.20 –	0.55	1.50	490 – 610	325	315	295	– 0 0	– 27 47
Class 3	SM490Y	A B	0.20	–	0.55	1.50	490 – 610	365	355	335	– 0	– 27
Class 4	SM520	A B	0.20	–	0.55	1.50	520 – 640	365	355	335	0 0	27 47
Class 5	SM570		0.18	–	0.55	1.50	570 – 720	460	450	430	–5	47

Note: (1) P,S ≦0.040%

(2) Class 5 Ceq≦0.44

Table 2.3 Extract from JIS for rolled steels for building structure (JIS G 3136)

Strength class (N/mm²)	Grade and class	Chemical composition (mass%) C Thickness t (mm) 6≤ t ≤50	C 50< t ≤100	Si	Mn	P	S	Ceq Thickness t (mm) Total Elongation [illegible]	Ceq < t ≤100	P_{CM}
400	SN400A	≤ 0.24	≤ 0.24	—	—	≤0.050	≤0.050	—	—	—
400	SN400B	≤ 0.20	≤ 0.22	≤ 0.35	0.60~ 1.40	≤0.030	≤0.015	≤ 0.36	≤ 0.36	≤ 0.26
400	SN400C	≤ 0.20	≤ 0.22	≤ 0.35	0.60~ 1.40	≤0.020	≤0.008	≤ 0.36	≤ 0.36	≤ 0.26
490	SN490B	≤ 0.18	≤ 0.20	≤ 0.55	≤ 1.60	≤0.030	≤0.015	≤ 0.44	≤ 0.46	≤ 0.29
490	SN490C	≤ 0.18	≤ 0.20	≤ 0.55	≤ 1.60	≤0.020	≤0.008	≤ 0.44	≤ 0.46	≤ 0.29

Strength class (N/mm²)	Grade and class	Yield point or proof stress (N/mm²) Thickness t (mm) 6≤ t <12	12≤ t <16	16	16< t ≤40	40< t ≤100	Tensile strength (N/mm²)	Yield ratio (%)	Elongation (%) Thickness t (mm) No. 1A specimen t ≤16	No. 1A specimen 16< t ≤40	No. 4 specimen 40< t	Charpy absorbed energy vE (0°C) (J)	Reduction of area in thickness direction (%)	Ultra-sonic testing
400	SN400A	235 ≤	235 ≤	235 ≤	235 ≤	215 ≤	400~510	—	17≤	21≤	23≤	—	—	—
400	SN400B	235 ≤	235~355	235~355	235~355	215~ 335	400~510	≤ 80 when upper limit of yield point is specified	18≤	22≤	24≤	27≤	—	Option for 13 ≤ t
400	SN400C	Out of scope of standard	Out of scope of standard	235~355	235~355	215~ 335	400~510	≤ 80 when upper limit of yield point is specified	18≤	22≤	24≤	27≤	25≤	JIS G 0901 Grade Y
490	SN490B	325 ≤	325~445	325~445	325~445	295~ 415	490~610	≤ 80 when upper limit of yield point is specified	17≤	21≤	23≤	27≤	—	Option for 13 ≤ t
490	SN490C	Out of scope of standard	Out of scope of standard	325~445	325~445	295~ 415	490~610	≤ 80 when upper limit of yield point is specified	17≤	21≤	23≤	27≤	25≤	JIS G 0901 Grade Y

- Steels for

  Building construction
  SN series

$$\text{Yield ratio} = \sigma_{\text{Yield}} / \sigma_{\text{Tensile}}$$

Large ratio decrease the compliance of structures such as building .

- *SN steel has sufficient plastic deformation before fracture that prevent catastrophic events*
- *Yield ratio (YS/TS) is specified 0.8 or less for SN steels*
- *Reduction in thickness direction also specified for Class C steel to prevent laminar tear when loaded in thickness direction*

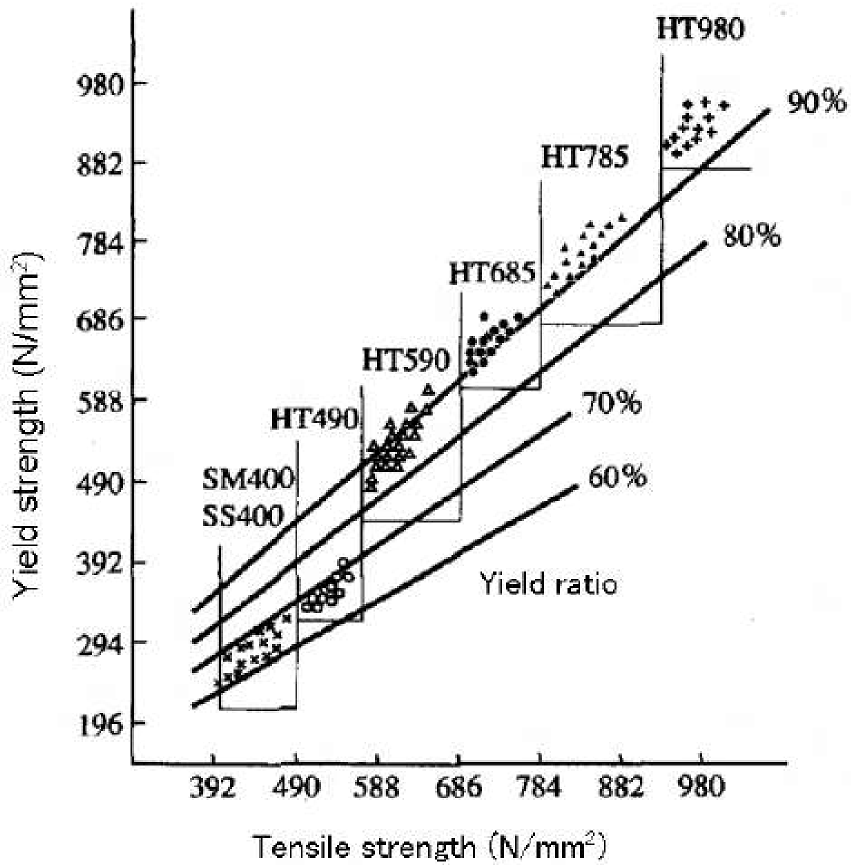
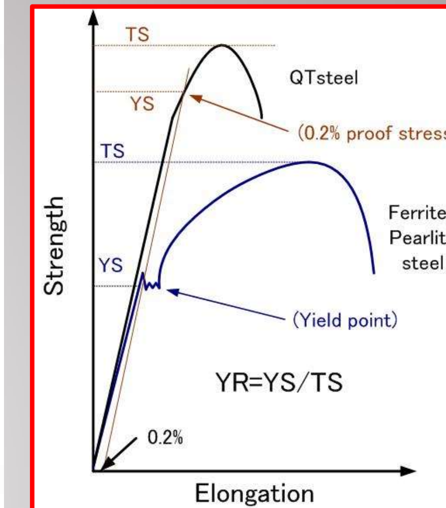
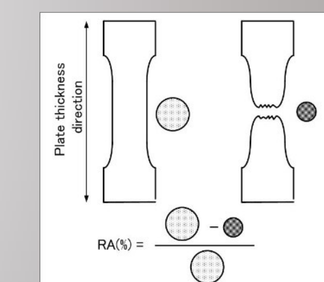


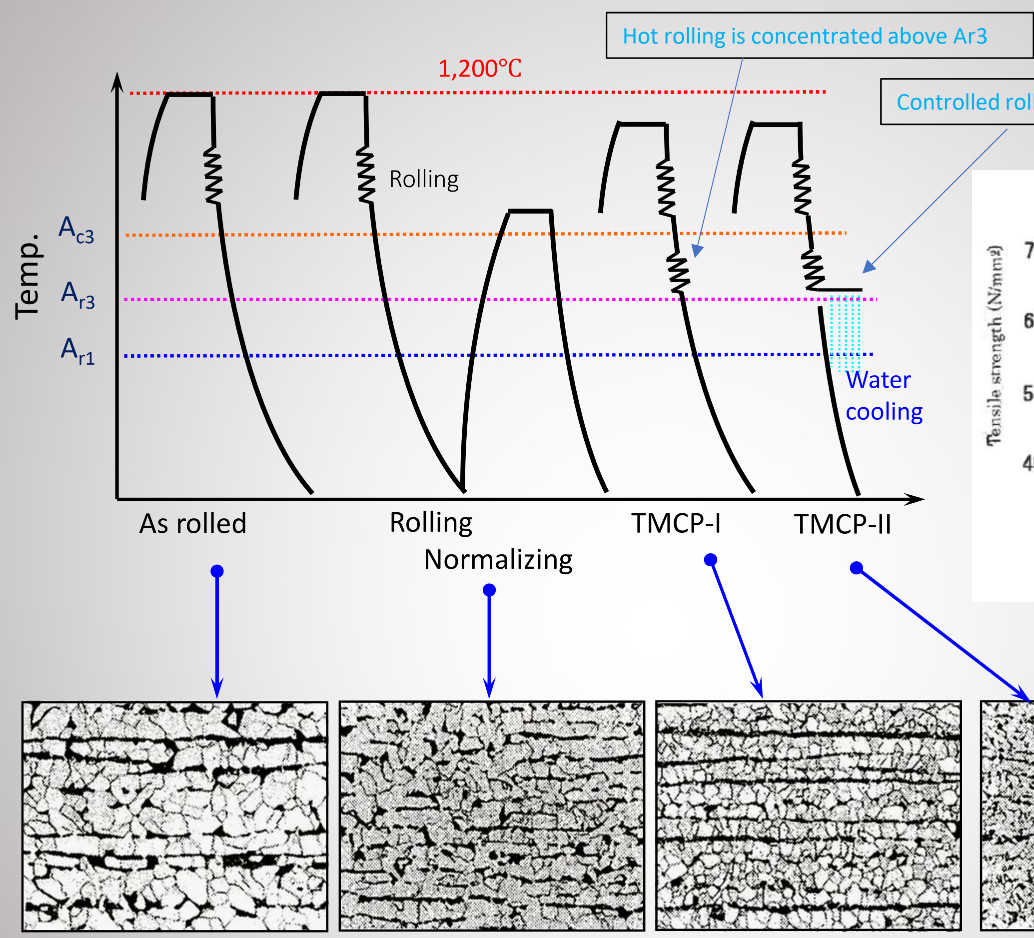
Fig. 2.4 Ratio of TS and YP

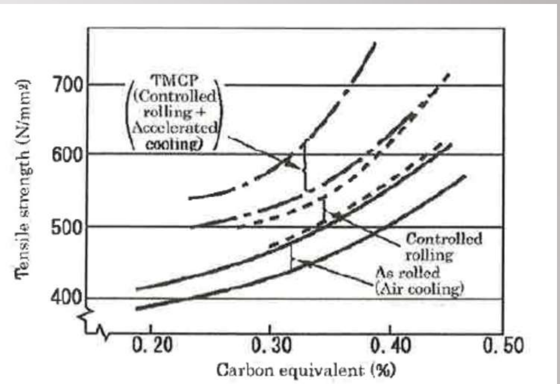




$$\phi = \frac{A_0 - A_f}{A_0} \times 100 \quad (\%)$$

2) High Tensile Strength Steels (TMCP Steels)





Relation between carbon equivalent and strength for TMCP steel

（HT490）

* TMCP （Thermo-Mechanical Control Process)

TMCP Steels

- The contents of carbon and alloying elements, the carbon equivalent can be reduced in TMCP steel
- Strengthened by grain refining
- The weldability of TMCP steels is improved
- Necessary to take precautions to the maximum heating temperature in line heating for the correction of welding distortion

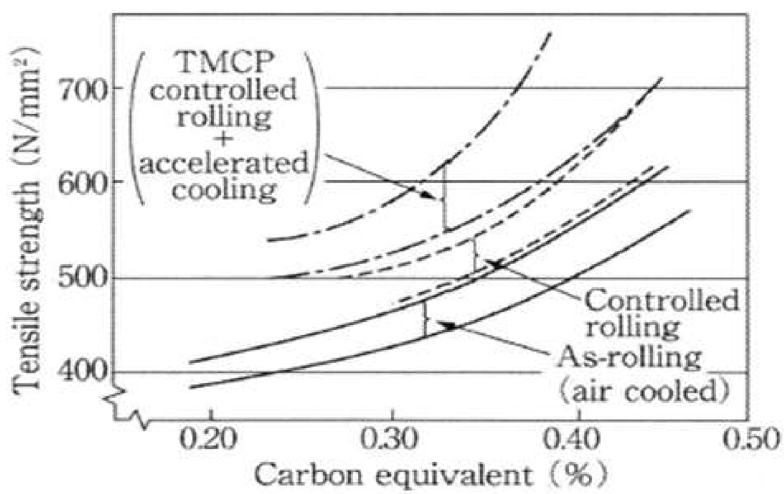


Fig. 2.1.7 Relation between hot rolling process, carbon equivalent, and tensile strength

JIS standard and steels

- Steels (SS, SM, SN)
- High strength steel
- Low temperature service steel
  - Low carbon steel (SLA series)
  - Al killed steel (Si-Mn type)
  - Ni steels
  - Aluminum alloys
  - Austenite stainless steel (304, 304L)
  - Inver (34%Ni-Fe)
- High temperature service steel
  - SB series : ex. for Boilers (Mo)
- Others
  - SMA series : Atmospheric corrosion resisting

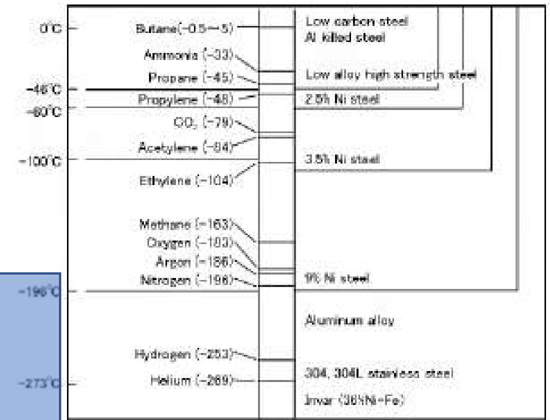


Fig. 2.5 Boiling point of liquefied gasses and low temperature service steel

3) Low Temp. Service Steel

- *Structural steel developed for large vessels and equipment for transportation/storage of liquefied gas.*
- *Service temp. for cryogenic vessel is considered as boiling temp. at atmospheric pressure of stored liquefied gas*
- *Ni improve the notch toughness of steel at low temp. most significantly*

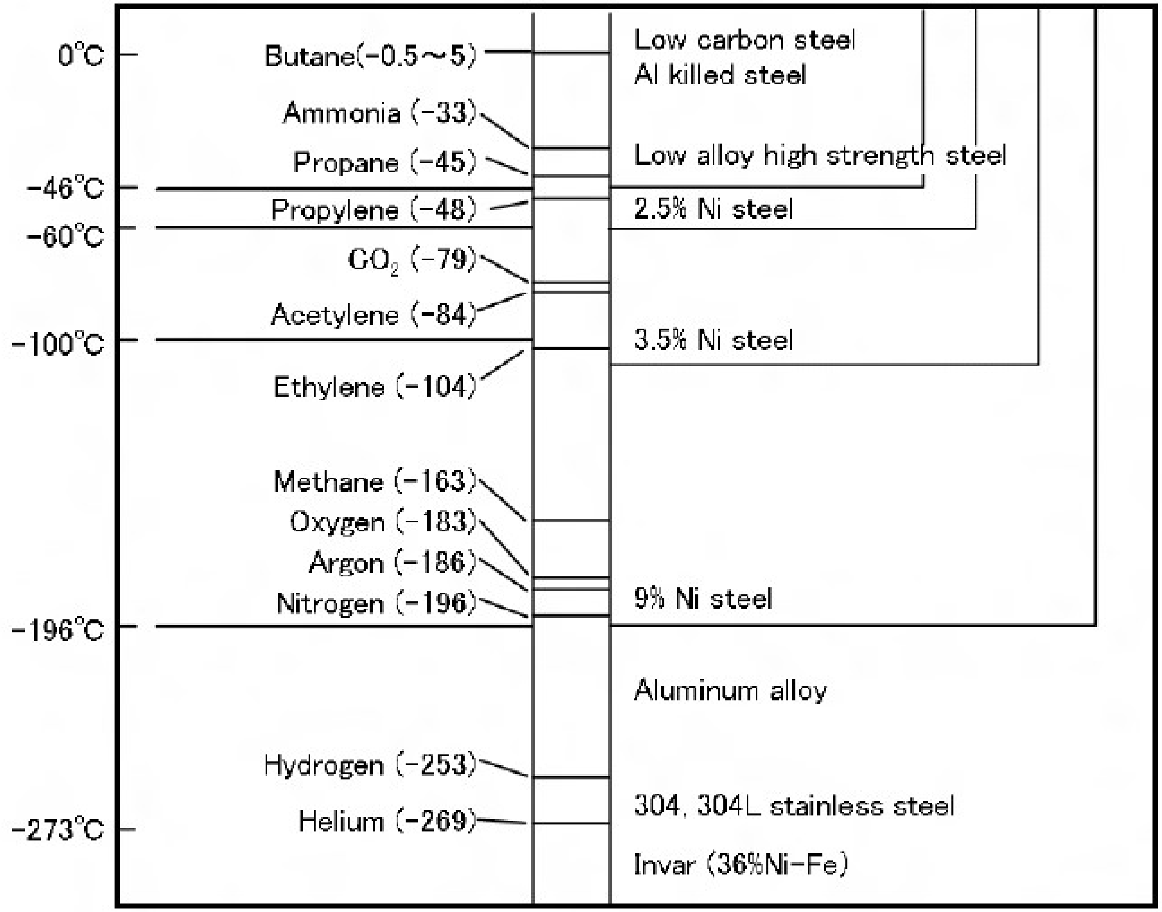


Fig. 2.5 Boiling point of liquefied gasses and low temperature service steel

Table 2.4 Low temperature service carbon steel for pressure vessels (Extracted from JIS G 3126:2004)

Symbol	Yield strength or proof stress N/mm²		Tensile strength N/mm²	Lowest temperature for use °C	Heat treatment	Charpy V-notch impact test temperature[**] °C			
	≦40	>40				6≦t<8.5	8.5≦t≦12	12<t≦20	20<t
SLA235A	≧235	≧215	400 – 500	-30	Normalizing [*]TMCP	-5	-5	-5	-10
SLA235B				-45		-30	-20	-15	-30
SLA235A	≧325		440 – 560			-40	-30	-25	-35
SLA235B				-60	QT [*]TMCP	-60	-50	-45	-55
SLA365	≧365		490 – 610			-60	-50	-45	-55
SLA410	≧410		520 – 640		TMCP or QT	-60	-50	-45	-55
Specimen size for Charpy impact test (t×w) mm						10×5	10×7.5	10×10	10×10

[*]Application of TMCP shall be as agreed upon by the parties concerned with delivery.

[**]Absorbed energy should be more than 1/2 of the maximum value. Where, the maximum value shall be the average value obtained from three specimens whose fractured surface gives 0 % brittle fracture ratio.

- High temperature service steel (Mo, Cr, Mn)

Types

- Carbon steel
- 0.5Mo steel, Mn-0.5Mo steel
- 1Cr-0.5Mo steel
- $1^{1}/_{4}$Cr- 1Mo steel

Requirements

- Strength at high temperature
- Creep deformation
- Corrosion
- High pressure H_2

- *Used for Boiler and Pressure Vessels*
- *Molybdenum (Mo) is the most effective element to improve creep strength*
- *Chromium (Cr)improves creep strength and oxidation resistance through forming oxide film which stable at service temperature and also prevents hydrogen attack*

Low Preheating Temp. Steels

- “Crack Free“ HW450CF and HW490CF high strength steel plates with low susceptibility to cold cracking
- HT780 lowering the preheating temperature from 100C to 50C
- HT780 contains Cu of about 1% and is hardened by Cu precipitation caused by ageing at 600C after hot rolling, alloying elements can be reduced, the susceptibility to cold cracking of the Cu precipitated steel is very low

Steels with Lamellar tearing Resistance

- (T-joint, cruciform joint, corner joint, etc.) Subjected to large welding restraint stress in the thickness direction
- Related to the thickness-wise ductility of steel

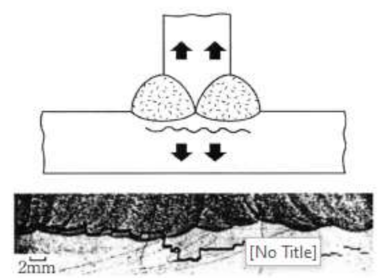


Fig. 2.1.10 An example of lamellar tearing

Table. 2.1.3 Target values of reduction of area in thickness direction in JIS G 3199

(unit : %)

Class	Average value for three specimens	Value for each specimen
Z 15	≧15	≧10
Z 25	≧25	≧15
Z 35	≧35	≧25

Type of Material Certificates

Type A (EN 10204 2.2) - Certificate
Confirm specification, on the basis of test results taken from the in-production testing of products of the same material and same manufacturing method
For carbon steel pressure containing parts in non-hydrocarbon services with an operating temperature above 0 degC and not in contact with hydrocarbon.

Type B (EN 10204 3.1B)
Confirm specification, on the basis of test carried out on the purchased material itself or on standard specified test specimens related to that material
Testing carried out by a testing center independent of production in the manufacturing work
For carbon steel pressure containing parts in hydrocarbon services with an operating temperature above 0 deg C and in contact with hydrocarbon services .

Type C (EN 10204 3.1C / 3.2)
Type B with the additional requirement that the tests shall be witnessed by an approved third-party independent inspector.
Certificates for Type C shall be valid only when stamped and signed by this third-party independent inspector.
For carbon steel pressure containing parts in hydrocarbon services with an operating temperature of 0 degC and below.
For pressure containing parts of low and high alloy steels (martensitic steels, ferrite and austenitic stainless steel, duplex stainless steel, etc.), nickel alloy (copper-nickel, Monel, Incoloy, nickel aluminum bronze, etc.), titanium.

Notch Toughness of Steel

- Deoxidizing
- Chemical Composition
  - Decrease C and Increase Mn – improve notch toughness
  - Mn, Ni, Al and Ti improve notch toughness
  - C, P and S deteriorate notch toughness
- Heat Treatment
  - Improve microstructure and notch toughness
  - As Rolled < Normalized Steel <QT Steel (tempered martensitic structure)
  - PWHT of QT steel – deteriorate notch toughness – PWHT embrittlement
- Microstructure / Grain Size
  - Notch toughness becomes better as ferritic grains become smaller
  - TMCP steel – hot rolling at lower temp – ferritic grains so fine
  - Al or Ti refine austenitic and ferrite grains
- Hot and Cold Working
- Gas Cutting
- Welding Heat

Fine Grained Metal
- *Generally have better mechanical properties, making them suitable for service at room temp. and below*

Coarse Grained Metal
- *Generally perform better at high temp. service*

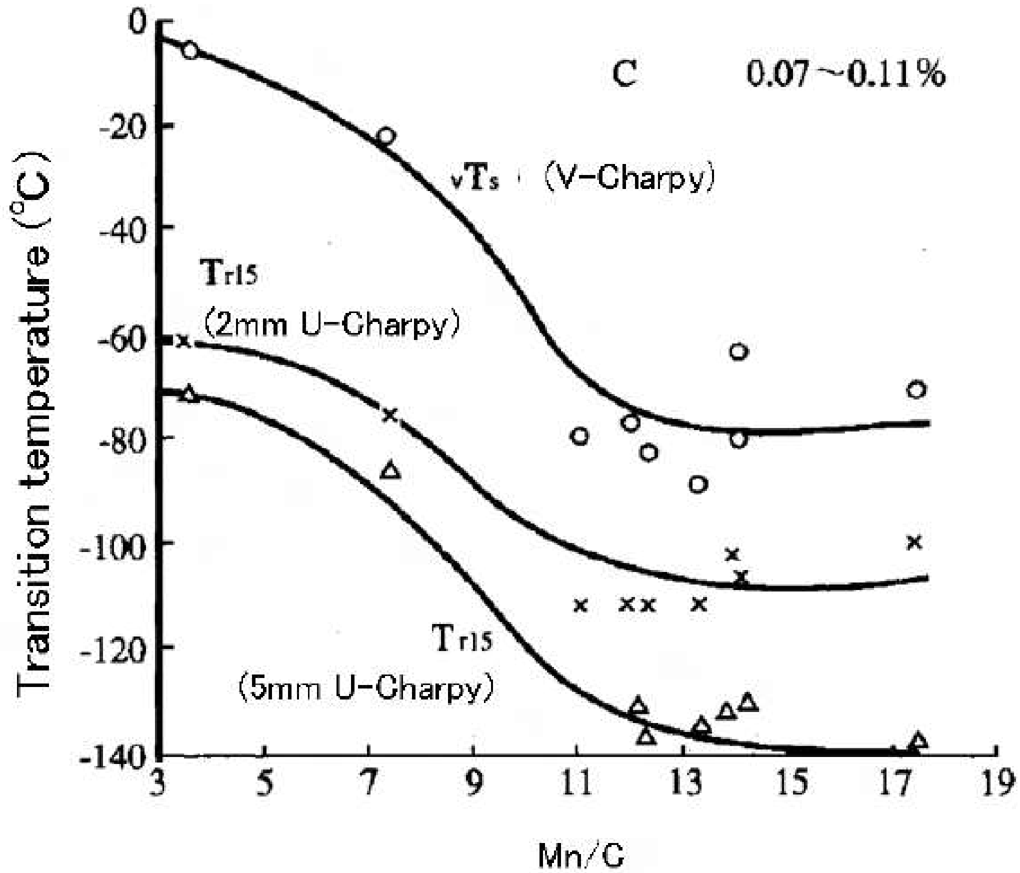


Fig. 2.6 Effect of Mn/C on transition temperature

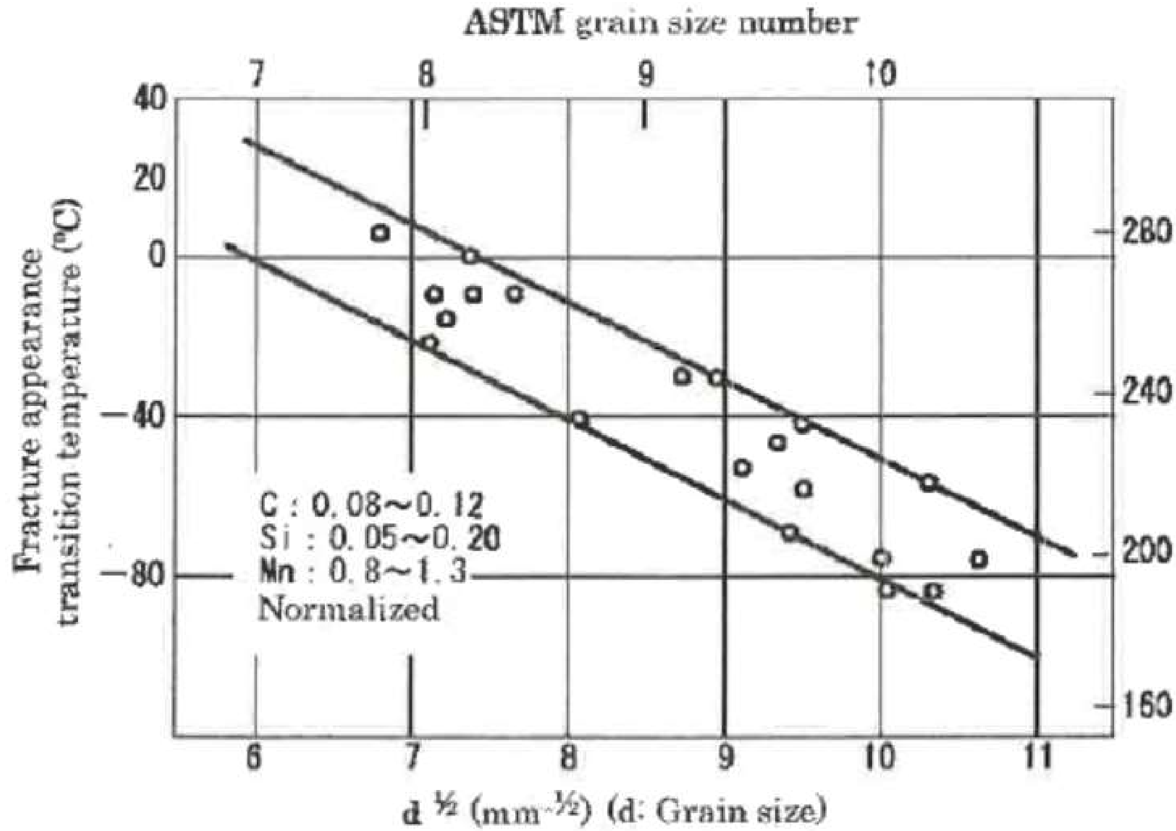


Fig. 2.8 Relation between fracture appearance transition temperature obtained by Charpy test and ferritic grain size

Toughness of Weld Metal

- The toughness of weld metal decreases unidirectionally as the nitrogen content in the weld metal increases
- Welding with the arc length longer than necessary or failure in taking the measures for windbreak causes the increase in nitrogen

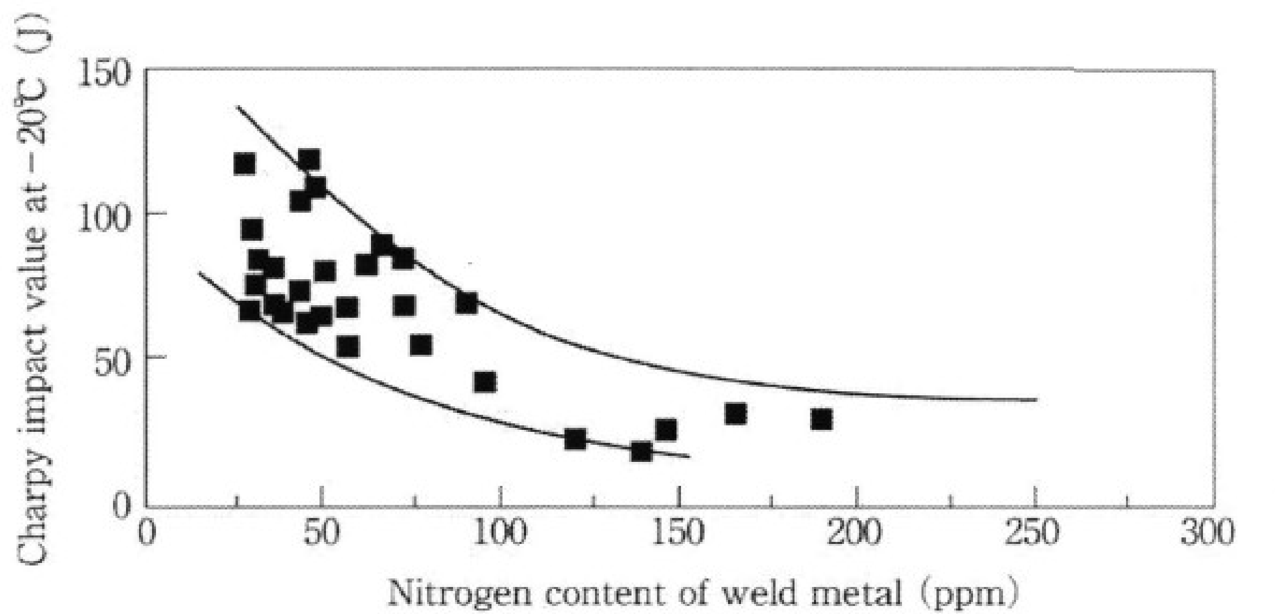
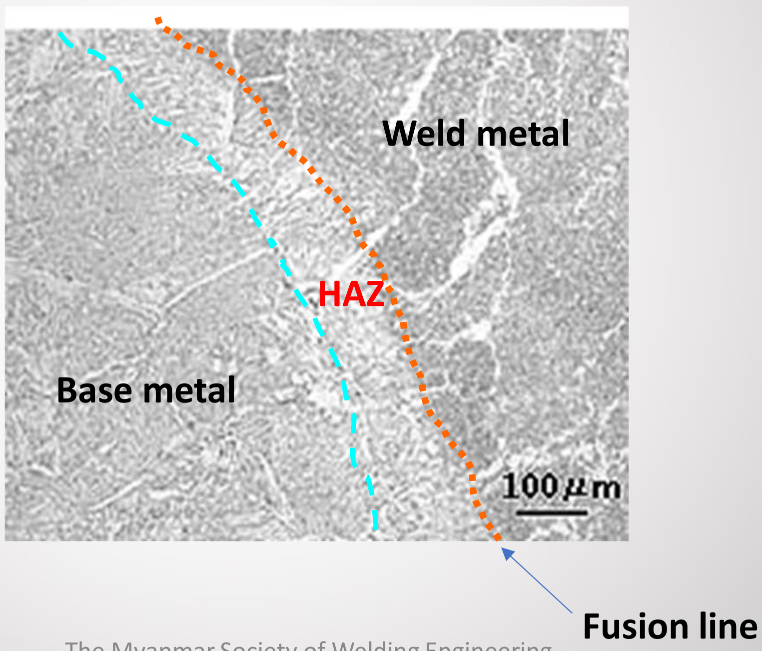


Fig. 2.2.20 Relation between toughness and nitrogen content of weld metal [49]

Heat Affected Zone – HAZ

- HAZ (Heat Affected Zone) – Adjacent to weld, no melting occurs but extremely high temp can be reached and whose microstructure or mechanical properties altered by welding heat
- Cooling rate in HAZ is the most rapid due to contact quenching phenomenon
- HAZ properties depend on Welding heat input and Cooling rate (heat transfer rate in base metal) – *The width of HAZ is function of the heat input*
- Microstructure and hardness of HAZ continuously changes depending on the distance from fusion line



Heat Input

Quantity of heat supplied by the arc per unit weld length

(unit: Joule / cm)

$$H = \frac{I \times V}{v} \times 60$$

I : welding current (Ampere)

V: arc voltage (Volt)

v: welding velocity (cm/min)

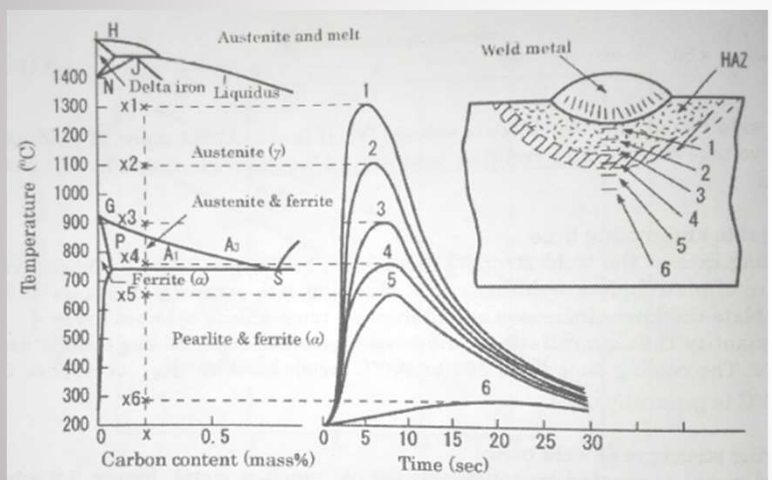


Fig. 2.10 Schematic change in structure in heat affected zone of carbon steel during welding

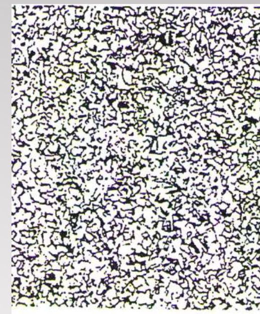
Table 2.6 Microstructure of heat affected zone of carbon steel corresponding to Fig. 2.10

Name	Approximate heating temperature range	Note	Position
Weld metal	Above melting temperature	Melting and solidification zone	—
Coarse grained zone	> 1250°C	Coarse grained zone which is likely to become hard and cause cracking	1
Mixed grain zone (Intermediate grain zone)	1250~1100°C	Medium size grain zone between coarse grained and fine grained zones, having intermediate characteristics	2
Fine grained zone	1100~900°C	Grain refining through normalizing heat treatment, having good mechanical properties such as toughness	3
Spheroidal pearlite zone (Dual phase zone)	900~750°C	Only pearlite is transformed or spheroidized. Slow cooling makes toughness good, while rapid cooling generates island-like martensite (MA constituents) and deteriorates toughness.	4
Embrittled zone	750~200°C	Sometimes embrittled by precipitation and strain aging, showing no change in microstructure	5
Non-heat affected zone of base metal	200°C ~ room temperature	Base metal that is not affected by arc heat	6

- *At high peak temp., near the weld interface (1), diffusion is more rapid, and solute atoms (carbon) dispersed uniformly in Austenite. In addition Astenite grain growth occurs. Likely to become hard and cause cracking.*
- *At intermediate peak temp. (2), homogeneity and grain size of Austenite are between these extremes.*
- *At lower peak temp., slightly above Austenite transformation temp. (3), carbides may not completely dissolve in the Austenite and solute atoms not diffuse far from original site of carbides. Hence austenite contains areas of alloy content. In addition Austenite possesses a fine-grained micro structure, having good toughness.*

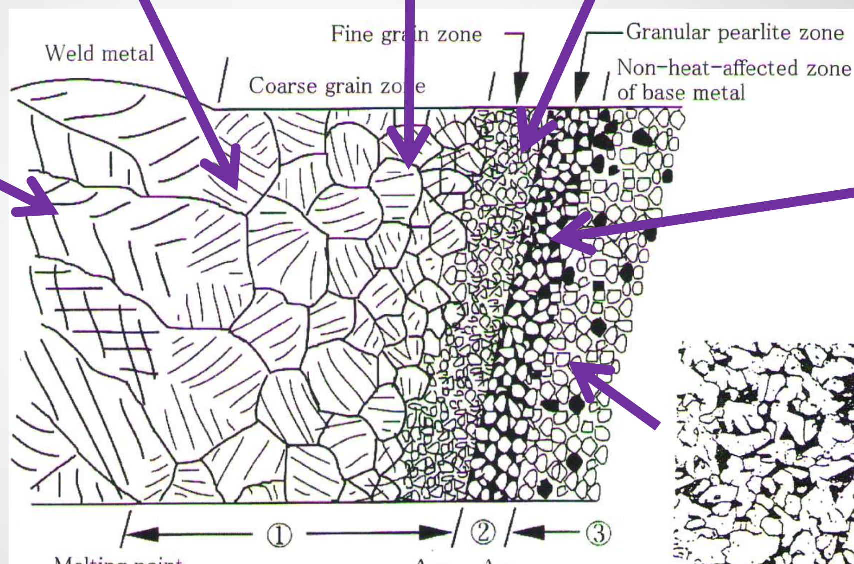
(b) Zone near to weld interface (1500–1300℃)
(Weld metal and coarse grain zone)

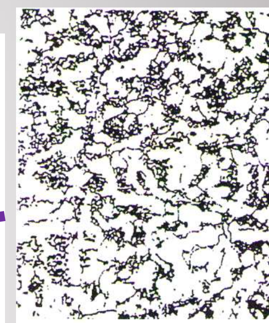
(c) Mixed-size grain zone (1250–1100℃)



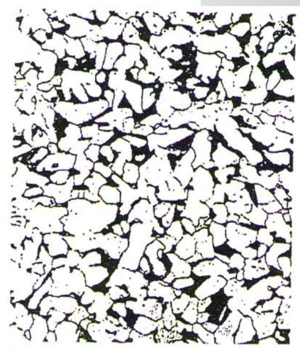
(d) Fine grain zone (1100–900℃)

(a) Weld metal (1500℃ or higher)





(e) Granular pearlite zone (900–750℃)



(f) Non-heat-affected zone of base metal
(700℃ to room temperature)

Weldability and Weld Defects

Weldability

Capacity of a material to be welded

- Under imposed fabrication conditions into a specific suitable welded structure (No weld defects)
- To perform satisfactorily in the intended service (Satisfied mechanical properties of weld joint)

Affected by

- Chemical composition primarily
- Section shape and thickness
- Cleanliness of the surfaces to be joined
- Mechanical properties of the metal

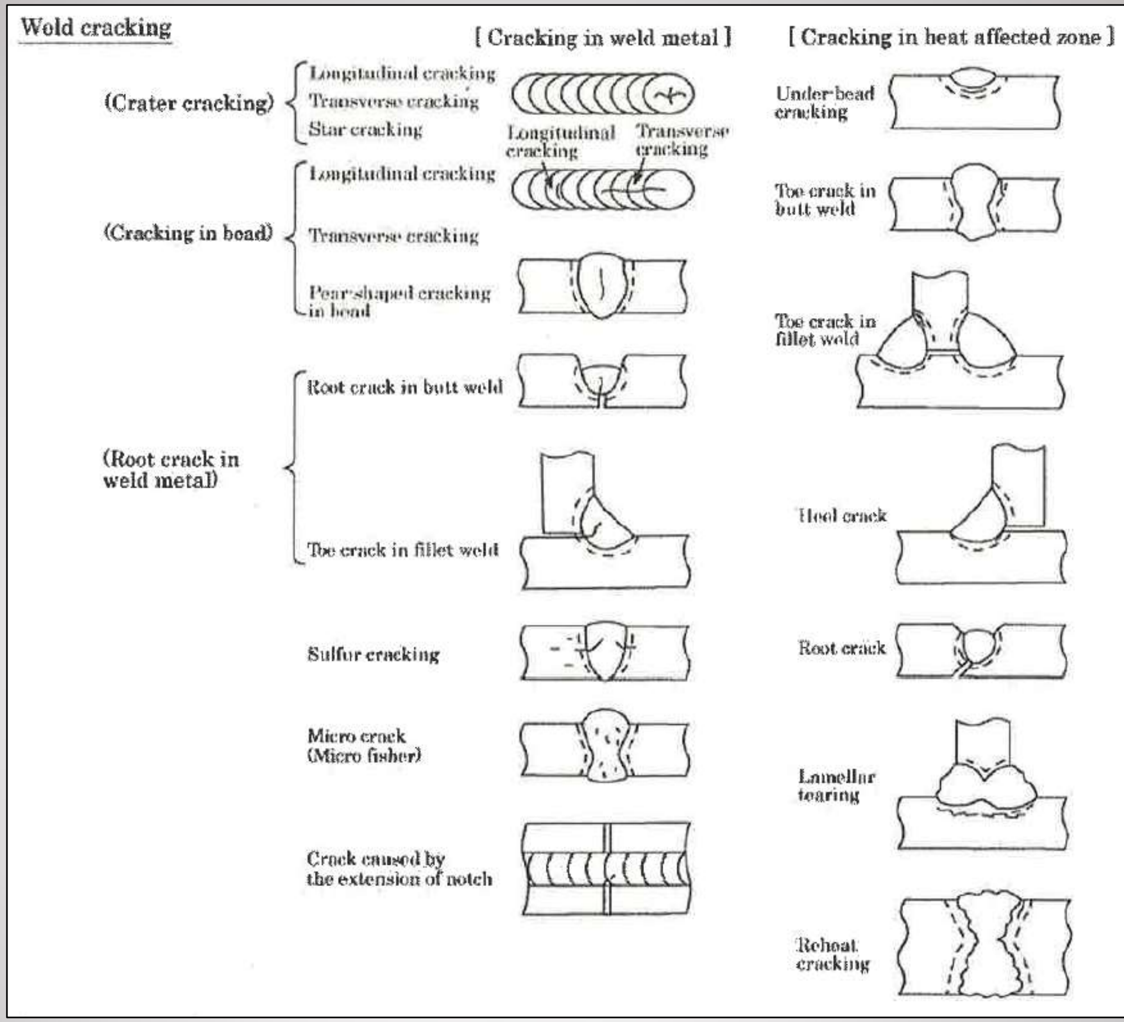
Unweldable

- Extraordinary precaution are necessary
- Unweldable material welded under tight controls with vigorous inspection and acceptance criteria

Weld Defects

A discontinuity or discontinuities that by nature or accumulated effect render a part or product unable to meet minimum applicable acceptance standards or specifications

- Cracking
- Blowhole (Porosity)
- Slag inclusion
- Incomplete fusion
- Overlap, Undercut and etc.


Weld cracking
[Cracking in weld metal]
[Cracking in heat affected zone]
(Crater cracking)
Longitudinal cracking
Transverse cracking
Star cracking
Longitudinal cracking
Transverse cracking
(Cracking in bead)
Longitudinal cracking
Transverse cracking
Pear-shaped cracking in bead
(Root crack in weld metal)
Root crack in butt weld
Toe crack in fillet weld
Sulfur cracking
Micro crack (Micro fisher)
Crack caused by the extension of notch
Under-bead cracking
Toe crack in butt weld
Toe crack in fillet weld
Heel crack
Root crack
Lamellar tearing
Reheat cracking

Other cracking

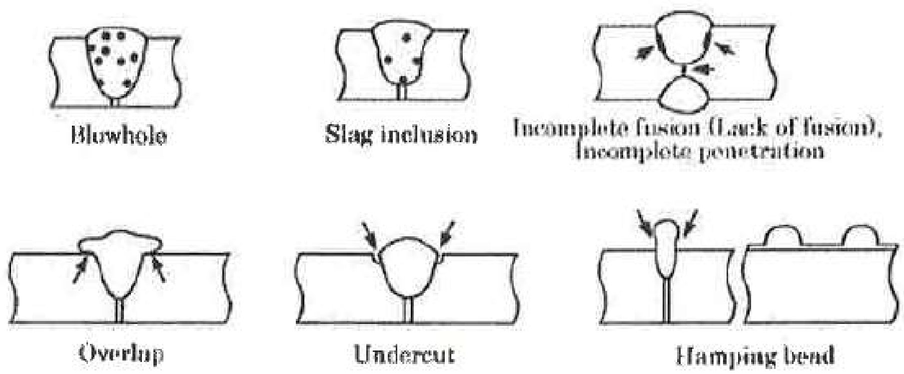


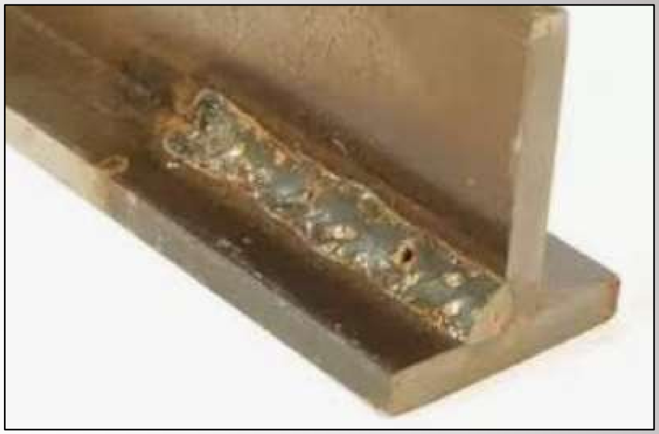
Fig. 2.17 Types and classification of welding defects

Blowhole / Porosity

(Gas Metal Reaction)

Factors Generating Blowhole

1) Blow holes - Gases trap in weld metal and can not rise to the surface of weld metal – CO, H2 and N2
2) Paint and rust on the surface of material to be welded
3) Repaid cooling / Welding HI and Speed



Concept for preventing Blowhole

1) Make sufficient shielding of weld pool
2) Make sure cleaning of metal surface prior welding
3) Control welding HI, speed (max. 2 m/s) and pre-heat temp and adequate
4) electrode manipulation (avoid excessive wide waving – Max. 3 times as electrode dia.)

- *Diatomic gas molecules are broken down into in the high temp. of welding atmosphere*
- *Gas atoms dissolve in liquid metal extremely fast at temp. of 1650C and higher*
- *Generally, react with intentionally added deoxidizers Mn, Si and Al and oxides form a slag and float to the weld surface or precipitate in the metal as discrete oxides*
- *If no sufficient deoxidizers, soluble oxygen will react with soluble carbon to produce CO or CO2*
- *Gas molecules will be rejected during solidification and produce porosity*
- *Hydrogen atoms are soluble in liquid steel and less soluble in solid steel*
- *Excessive hydrogen that is rejected during solidification will cause porosity*

Blowhole / Porosity

(Gas Metal Reaction)

Source of Hydrogen

- *Air (Atmosphere)*
- *Moisture in electrode coating and loose flux*
- *Solid solution in non-ferrous metals or surface oxide*
- *Organic lubricating compounds (wire drawing and stamping operation)*

Source of Oxygen

- *Air (Atmosphere)*
- *In GMAW intentionally added to stabilize the arc*
- *Dissociation of water vapor, CO_2 or metal oxide*

Source of Nitrogen

- *Air (Atmosphere)*
- *Purge gas*

Hot Cracking (Solidification Cracking)

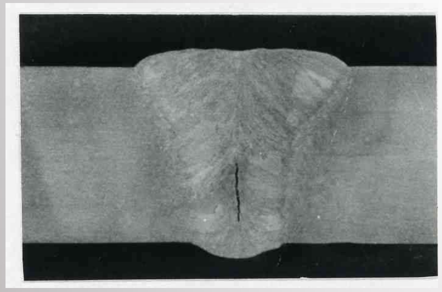
(Liquid Metal Reaction)

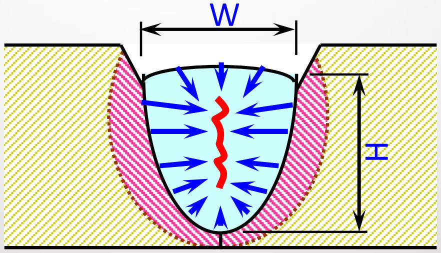
Factors Generating Hot Cracking

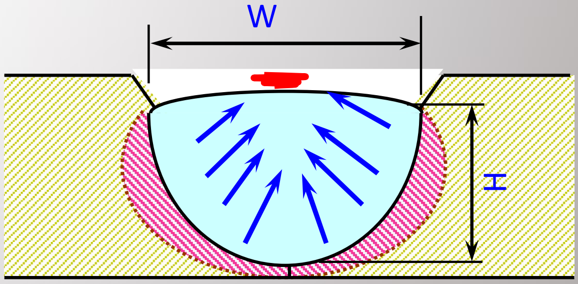
1) Impurities with low melting point exist in grain boundary such as P and S (low melting point phases that wet the dendrite surfaces)
2) Joint Shape with bead width excessively small
3) Shrinkage stress in weld metal or HAZ with poor ductility in the range of its solidification temp. (>1200C)
4) Micro cracks between the dendrites occurs at temp. close to solidification temp.
5) Repaid cooling / Welding HI and Speed

Concept for preventing Hot Cracking

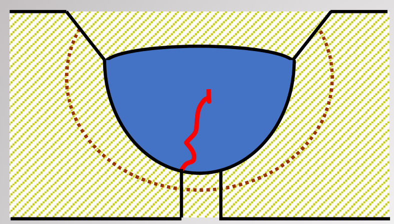
1) Reduce impurities such as P, S in the base metal and welding consumable
2) Make sure W/H is greater than 1
3) Not to generate excessive restraint stress (control plate thk, / groove shape / root opening)
4) Adequate Welding I, V, Speed, Pre-heat temp. and adequate electrode manipulation)
5) Mn and Si tend to reduce solidification cracking (this approach become less effective with increasing carbon content / medium or high carbon steel tend to have solidification crack even though Mn or Si increase)
6) Mn to C composition ratio of 30 or more
7) Austenitic stainless steel filler metal formulated – weld metal contains 2 ~ 8% ferrite at room temp.

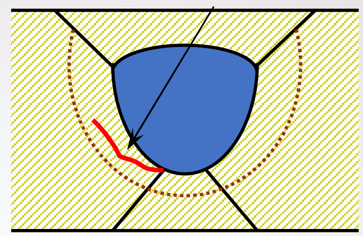


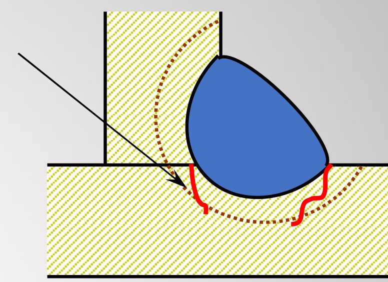


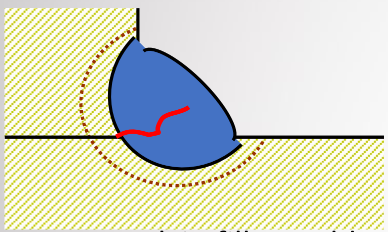


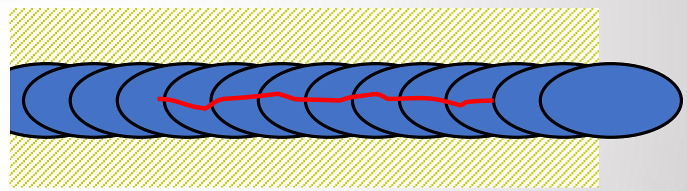
Cold Cracking (Delayed Cracking)

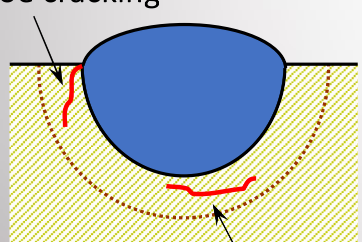

Root crack in butt weld

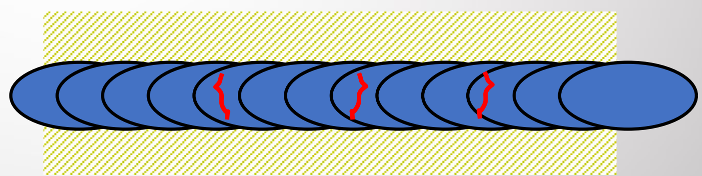

Heel crack


Toe cracking


Root crack in fillet weld

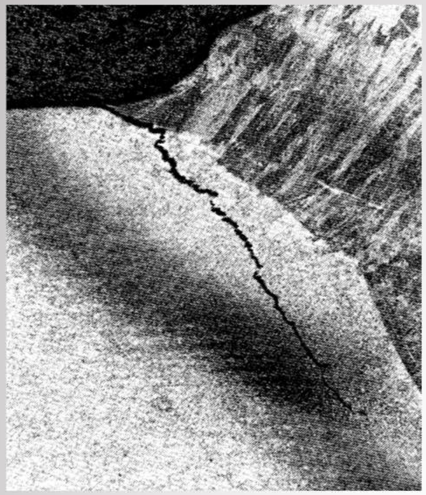

Longitudinal cracking




Transverse cracking

Cold Cracking *(Solid State Reaction)*

Cold cracking occurs when temp. decreased lower than 300F (consists of root/under bead/toe cracking in weld metal of HAZ) – After weld has cooled to ambient temp. which may be hours or even days after welding when dissolved hydrogen remains in weld metal



Factors Generating Cold Cracking

1) Hardening of HAZ *(Hardenable steel transformed to Martensite during rapid cooling)*
2) Diffusible hydrogen in weld *(Hydrogen that remains dissolved in solid steel)*
3) Tensile residual stress in weld

Concept for preventing Cold Cracking

1) Reduce Pcm value as much as low (not to generate Martensite in HAZ) / Decrease cooling rate (no Martensite forming in HAZ and hydrogen diffuse and leave weld metal) / Increase heat input / specify pre-heat temp / Preheat base metal
2) Use of low hydrogen electrode / post heating immediately after welding
3) Avoid large thickness and complication of shape of joint design to reduce restraint stress

$$Pc = P_{CM} + \frac{1}{60}H + \frac{1}{600}t \quad (\%)$$

$$P_{CM} = C + \frac{1}{30}Si + \frac{1}{20}Mn + \frac{1}{20}Cu + \frac{1}{60}Ni + \frac{1}{20}Cr + \frac{1}{15}Mo + \frac{1}{10}V + 5B \quad (\%)$$

Pc: Index for cold crack sensitivity in weld joint plate for cold crack sensitivity

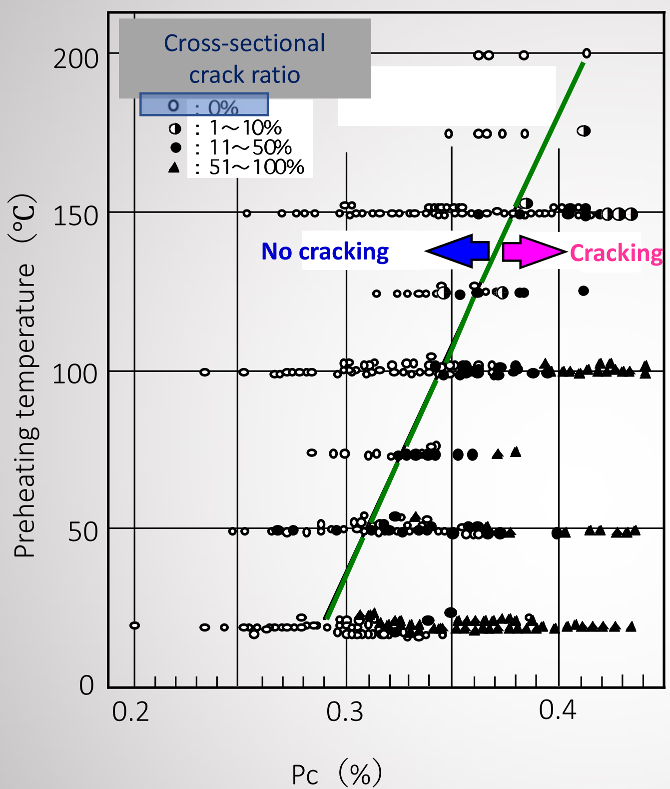
P_{CM}: Index of chemical composition of steel

H: quantity of hydrogen in the weld metal (ml/100g)

t: plate thickness (mm)

- *In plain carbon steel (low carbon steel) Austenite transforms to Pearlite (ferrite plus carbide) at relatively high temp. 700C*
- *Hydrogen is relatively soluble in austenite and almost insoluble in ferrite*
- *Hydrogen atoms have sufficient mobility to diffuse out of metal, hence relatively ductile and crack resistance in weld metal and HAZ even if cooling is rapid*
- *But in Hardenable steel Austenite transforms to Martesite at much lower temp. with rapid cooling*
- *Hydrogen atoms have lower mobility and trap in Martensite*
- *More crack sensitive in weld metal and HAZ*

Relation between Pc and preheating temperature



Weld Cracking Parameter (Pc)

$Pc = P_{CM} + H/60 + t/600$

Chemical composition of steel

Hydrogen

Plate thickness
(Cooling time/rate)

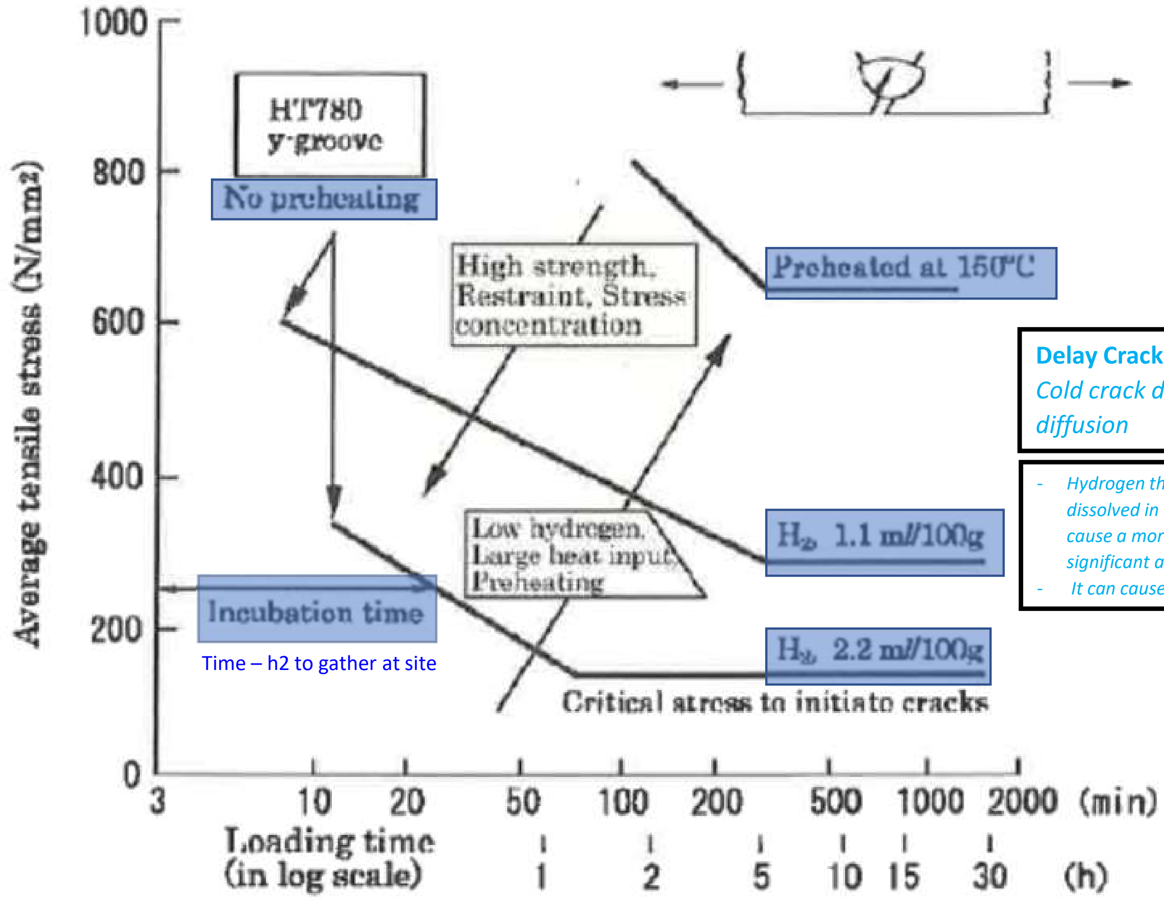
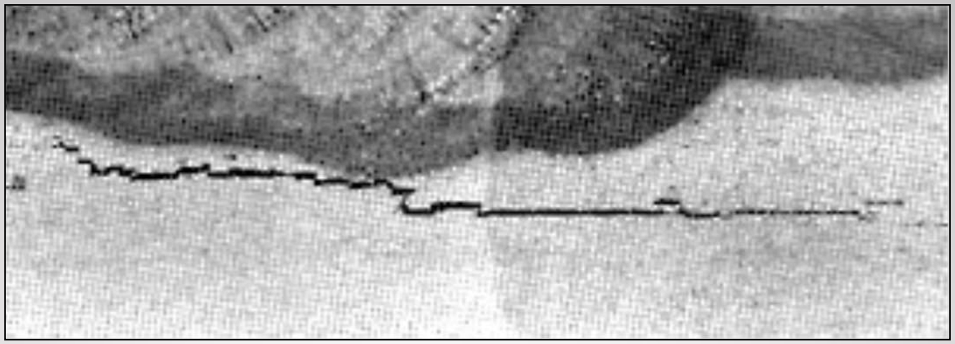


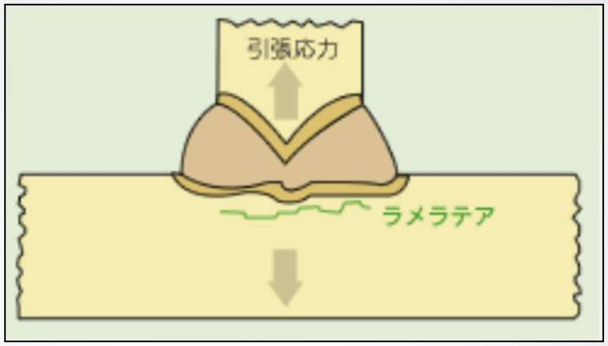
Fig. 2.20 Relation between loading time to cracking and applied stress in delayed cracking of HT780 steel caused by hydrogen

Delay Cracking

Cold crack delayed by H2 diffusion

- *Hydrogen that remains dissolved in the solid steel will cause a more problem when in significant amounts present*
- *It can cause delayed cracking*

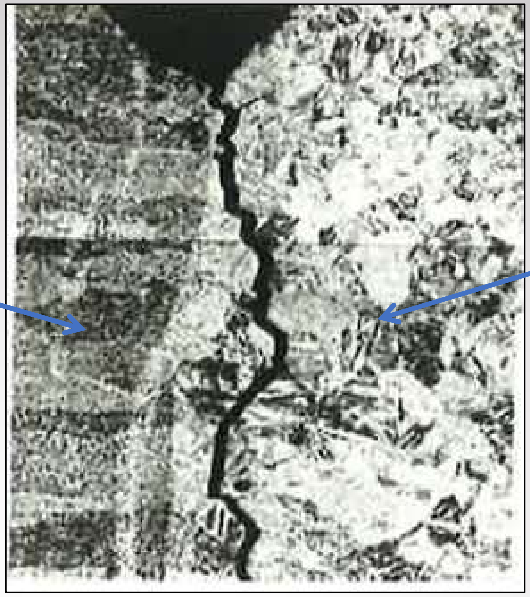




- *Hydrogen diffusing through the steel collects at non-metallic inclusions (such as manganese sulphide) oriented in the rolling plane*
- *Hydrogen atoms recombine to molecular (H2) at these site, essentially creating "micro bubble" in the metal*
- *Accompanying pressure increase leads to micro voids and cracks oriented along the rolling plane*
- *Cracks in different planes may become joined through transverse cracking giving the appearance of steps*

Lamellar Tearing

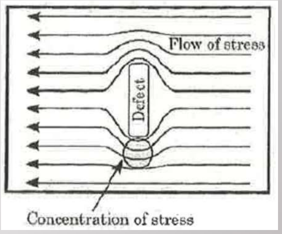
- Stepwise crack (HIC)
- In the direction parallel to the plate surface
- Prevention - To select S content low, the reduction area of thickness direction is high



Reheat Cracking

- Reheat cracks are initiated at the weld toe during stress relief annealing / PWHT
- Occurs at grain boundary of coarsened grain in HAZ
- Precipitation of carbides
- Stress concentration at weld toe

Effective measure to prevent reheat cracking is



To smooth weld toe by grinding (remove stress concentration)

Use appropriate steel with reduced amount of precipitation element such as Cr, Mo, V, Nb

Low heat input welding

Hydrogen Attack

- In the high-temperature high-pressure hydrogen atmosphere, hydrogen diffuses into steel, gathers at small defects, reacts with carbon in steel and forms methane

$$(Fe_3C + 4H \rightarrow 3Fe + CH_4)$$

- The internal pressure caused by methane bubbles causes cracking and blistering
- In the hydrogen attacked region, decarburization, micro fissures, blistering and cracking occur
- hydrogen attack is an irreversible phenomenon cannot be recovered by heat treatment

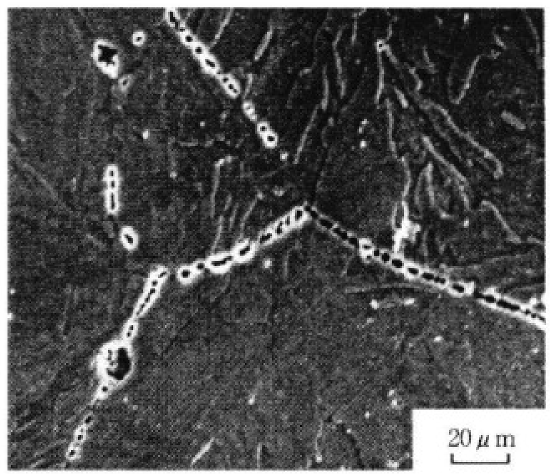


Fig. 2.2.33 Hydrogen attack [72)]

Thank you for your kind attention!

U Soe Thant