Welding Metallurgy

Weldability of Structural Steels

Lecture Scope

- Weldable grades of structural steel
- Factors affecting weldability
- Problem Areas
- Welding Procedures

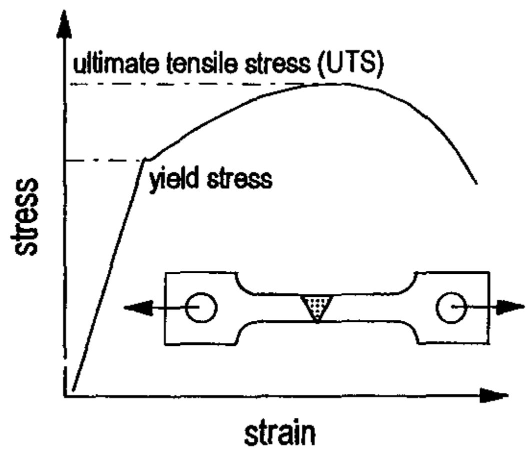
Weldability

Definition

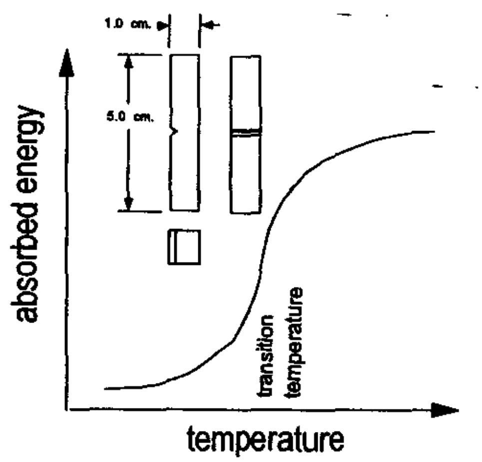
- *"The capacity of a metal to be welded under the fabrication conditions imposed into a specific suitably designed structure and to perform satisfactorily in service"* (American Welding Society)

Mechanical Properties of Welds

Tensile Strength



Notch Impact Toughness



Weldability of Steels

- Factors affecting weldability:
  - Steel composition & processing
  - Weld metal and HAZ properties
  - Choice of welding variables
  - Pre and post-weld processing

Steel Composition & Processing

- Weldable structural steels for use at ambient or moderately elevated temperatures fall into four categories:
  1. Carbon and carbon-manganese steel
  2. High-strength low-alloy (HSLA) steels
  3. Normalised and tempered high tensile steels
  4. Quenched and tempered high tensile steels

Main Alloying Additions in Steel

- Carbon is a potent solid-solution strengthening element in iron
- Carbon increases tensile strength but reduces ductility
- High carbon content promotes formation of hard, brittle microstructures on cooling from above the phase transformation temperature
- Manganese up to about 2% increases strength without reducing ductility, improves notch toughness, and reduces hot cracking.

Impurities

- Past steelmaking practices also left high impurity contents
- P, S, O, N
- P decreases toughness
- P and S form low-melting compounds that promote weld and HAZ solidification cracking
- O & N form dispersions of oxides and nitrides that strengthen the metal and reduce its ductility

Carbon and C-Mn Steels

- Traditional C-Mn structural steels relied on solid solution strengthening from carbon and manganese to reach a given strength
- Higher strength meant higher contents of these elements (C<= 0.35%)
- Combined with high impurity contents, led to poor weldability

Steel Developments

- In recent decades new steels have been developed which offer a combination of strength, ductility, and toughness
- Steps in achieving these benefits include some or all of: -
  - lower carbon contents,
  - lower impurity contents,
  - full deoxidisation, fine-grain practice,
  - small alloy additions of Ni, Cr, Mo, Cu, V, Ti, Zr, Al,
  - controlled rolling temperatures, and
  - normalising and quenching treatments

HSLA Steels

- Steels incorporating small alloy additions are known as high-strength low alloy (HSLA) steels or microalloyed steels.
- HSLA steels up to about 500 MPa UTS with carbon contents up to 0.25% and made with deoxidised fine grain practice are readily weldable.

Q&T Steels

- Steels that rely on quench and temper heat treatment to obtain very high strength are more susceptible to welding problems and require specific metallurgical expertise. e.g. G40.21 Grade 700Q, ASTM A 514.

Typical Steel Specifications

- Canadian Standards Association
  - CSA G40.21: Structural Quality Steels
    - Plates, shapes, hollow sections, sheet piling and bars for general construction and engineering purposes
    - Weldable grades of carbon-manganese steels and high-strength quenched and tempered steels

Steel Specifications

- American Society for Testing & Materials (ASTM)
  - A36 Structural Steel
  - A105 Forgings, carbon steel, for piping components
  - A106 Seamless carbon steel pipe for high-temperature service
  - A514 High yield strength, quenched and tempered alloy steel plate, suitable for welding
  - A515 Pressure vessel plates, carbon steel, for intermediate and higher-temperature service
  - A516 Pressure vessel plates, carbon steel, for moderate and lower temperature service
  - A706 Structural steel for bridges

Steel Specifications

- American Society for Mechanical Engineers
  - ASME adopts many ASTM materials specifications for use in its Boiler and Pressure Vessel Code, including those listed above
  - ASME material specifications are used for pressure vessels and piping in CANDU reactors
- American Petroleum Institute (API)
  - API 5L: Line Pipe
  - Pearlite Reduced Steels (PRS) & Acicular Ferrite Steels (AFS)

Properties of the HAZ

The response of the parent material and reheated weld metal in multi-pass welds to the weld thermal cycle determines the properties of the heat affected zone. The main factors are:

- Steel composition and processing
- Peak temperatures and cooling rates

The yield and ultimate strength of the HAZ are usually higher than the parent material, so the main properties of interest are hardness and toughness

HAZ Hardness

- Hardness is a measure of tensile strength and degree of embrittlement
- In C-Mn steels, HAZ hardness exceeding 350 Hv is considered excessive.
- HAZ hardness is determined by alloy content and cooling rate in the transformation temperature range.

HAZ Hardness

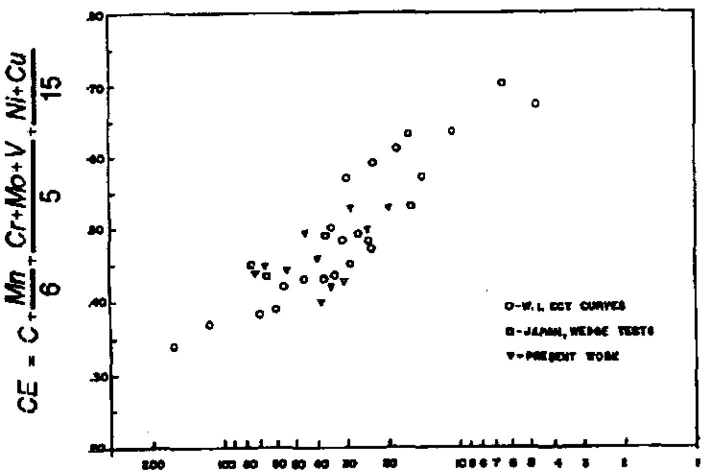
- Steel *hardenability* can be correlated with the *carbon equivalent (CE), e.g.:*

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

- Steels with CE below about 0.45 are readily weldable with appropriate procedures
- Preheat and weld heat input should be selected to give cooling rates that produce acceptable hardness
- CE greater than 0.45 indicates a need for caution

Effect of Cooling Rate

Cooling rate vs carbon equivalent for a HAZ hardness of 300 Hv



Cooling Rate at 540C (C/s)

Graville, B: The Principles of Cold Cracking Control in Welds, Dominion Bridge Company, Montreal, 1975.

Fracture Toughness of the HAZ

- The factors affecting toughness are
  - weld thermal cycle
  - grain coarsening temperature of the steel
  - transformation characteristics
  - alloy and impurity content

Fracture Toughness of the HAZ

- If the fracture toughness of the parent steel is low, the toughness of the HAZ is usually low, and conversely.
  - Fine grain practice and microalloying benefit the HAZ as well as the original material
- Low heat input welding procedures give a finer HAZ grain structure and better toughness in low CE steels
- However, in steels with a high CE content, HAZ hardness considerations set a minimum heat input.
- It is sometimes difficult to get adequate toughness in high CE steels

Weld Metal Tensile Strength

The factors that govern the tensile strength of the weld metal are

- Composition
  - C and Mn increase strength
- Ferrite grain size
  - Tensile strength increases as ferrite grain size is reduced

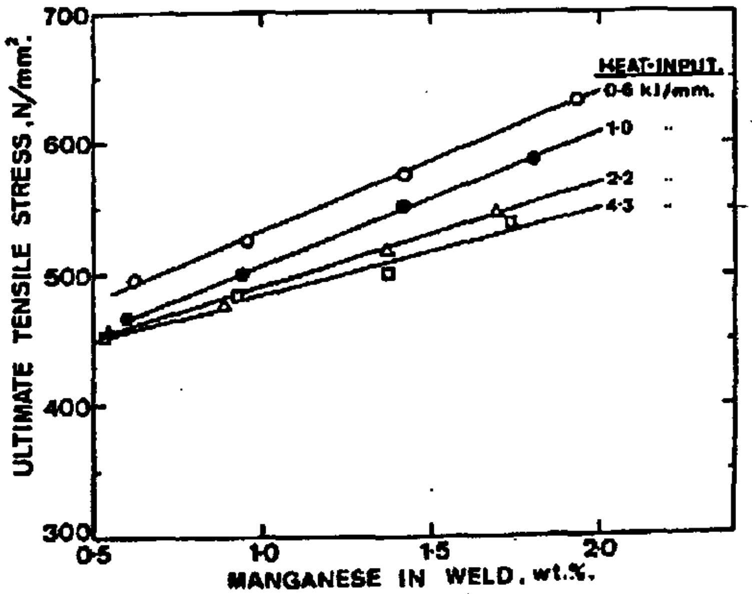
Weld Metal Toughness

- The notch toughness of weld metal varies with
  - grain size
  - the number of inclusions and other phases
- Notch toughness is reduced by
  - coarse, blocky pro-eutectoid ferrite grains
  - presence of retained martensite
  - numerous oxide and sulphur inclusions
- Optimum notch toughness is reached by:
  - Acicular ferrite weld metal microstructure, obtained through controls on heat input and alloy content
  - Deoxidized and desulphurized weld metal by use of basic fluxes.

Effects of Welding Variables

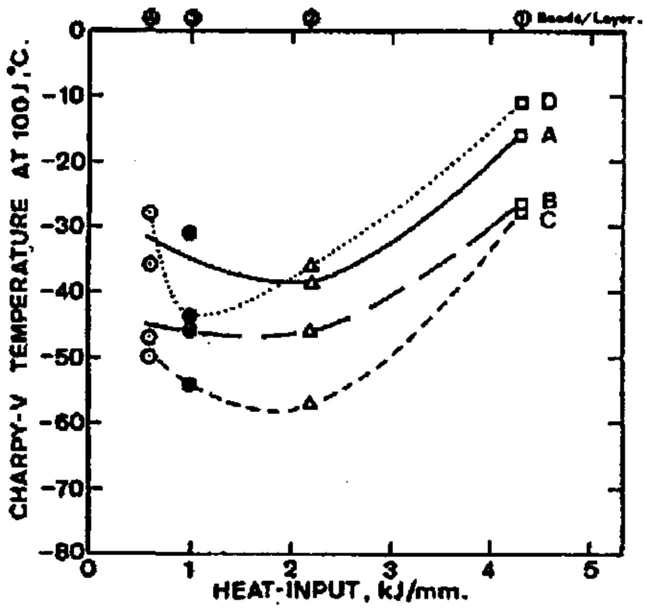
- Heat input
  - Increased heat input coarsens the weld metal solidification structure and decreases strength and toughness
  - High heat input processes such as SAW or ESW produce coarse-grained weld metal with relatively poor as-welded properties
  - SMAW, GMAW or GTAW give finer grain structure and better as-welded strength and toughness

Effect of Heat Input on UTS



Stout, R.D. Weldability of Steels Welding Research Council, New York

Effect of Heat Input on Notch Toughness

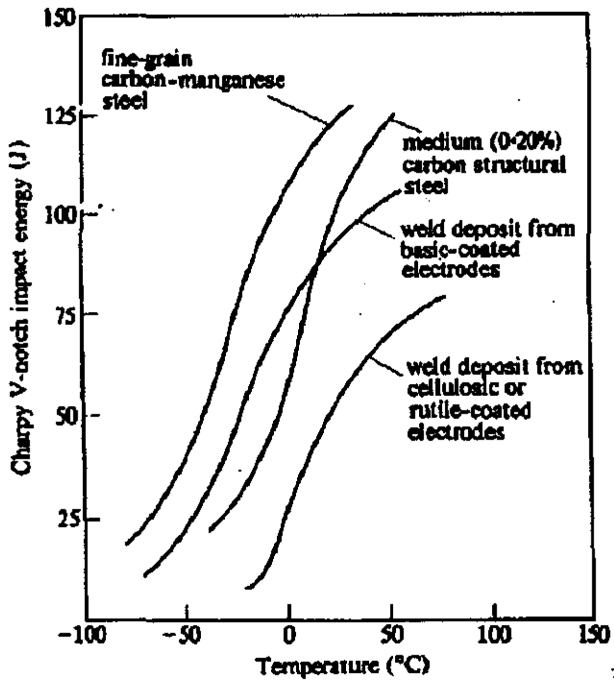


Stout, R.D. Weldability of Steels Welding Research Council, New York

Effect of Flux Type

- Flux type
  - Fluxes or slags that leave high weld metal oxygen contents give lower weld metal toughness.
  - Basic fluxes reduce weld metal sulphur and oxide inclusion content and give improved notch toughness and lower transition temperatures

Effect of Flux Type on Toughness



Lancaster, J.F. Metallurgy of Welding George Allen & Unwin, London

Welding Procedures

- C-Mn and HSLA steels up to CE 0.45 and UTS< 500 MPa are weldable by any arc welding process with appropriate procedures
- The table below gives general recommendations for preheat and interpass temperatures for typical steels

Steel Spec	Carbon	Thickness (mm)	Min Preheat & interpass temp, other than low-hydrogen	Min preheat & Interpass temp, low- hydrogen	PWHT
A 516 Gr 70	<.31%	10	> 50 C	>0 C	optional 600-675 C
		19	>100 C	50 C	optional 600-675C
		75	175 C	150 C	ASME Code req'd
A36	<.25%	25	>0 C	>0 C	Optional 600-675 C
		75	150 C	100 C	Optional 600-675C

Welding Problem Areas

- Cracking
  - Solidification Cracking
  - Hydrogen Induced Cracking
  - Lamellar Tearing
  - Reheat Cracking
- Porosity and Inclusions

Solidification Cracking

- Solidification cracks develop at elevated temperature during the latter stages of solidification
- In low-carbon steels, the first phase to solidify from the melt is delta ferrite. This transforms to austenite below 1500 C
- Elements such as sulphur, phosphorus and boron are less soluble in austenite than in the delta ferrite. They tend to segregated to the boundaries of the primary austenite grains
- The resulting low-melting point films promote intergranular weakness and may cause cracking in the presence of thermal strains
- Solidification cracking is *intergranular* with respect to the primary austenite grains.

Solidification Cracking-Avoidance

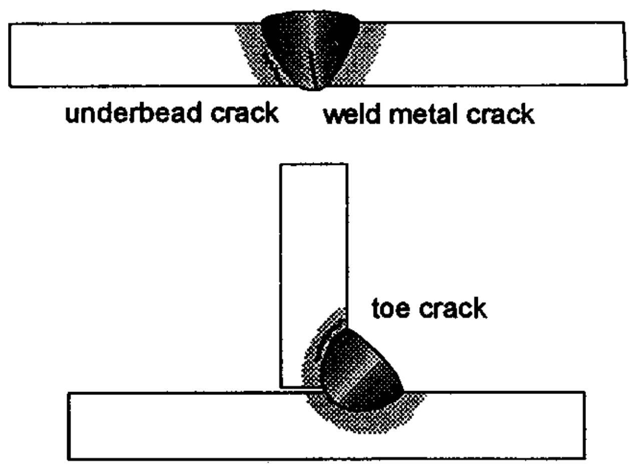
Solidification cracking is minimised by:

- maintaining a low carbon content in the weld deposit
- keeping sulphur and phosphorus as low as possible
- ensuring that manganese, which inhibits the effect of sulphur, is high enough to allow for possible dilution (and ingress of sulphur) from the base material.
- choosing welding parameters to avoid "centreline" type solidification structures.

Hydrogen Induced Cracking

- Steels at ambient temperatures may suffer from hydrogen embrittlement.
- Hydrogen embrittlement can result in cracking in welds called *hydrogen induced cracking* or *cold cracking.*

Typical Forms of HIC



Causes of HIC

HIC in welds occurs in the presence of four predisposing factors:

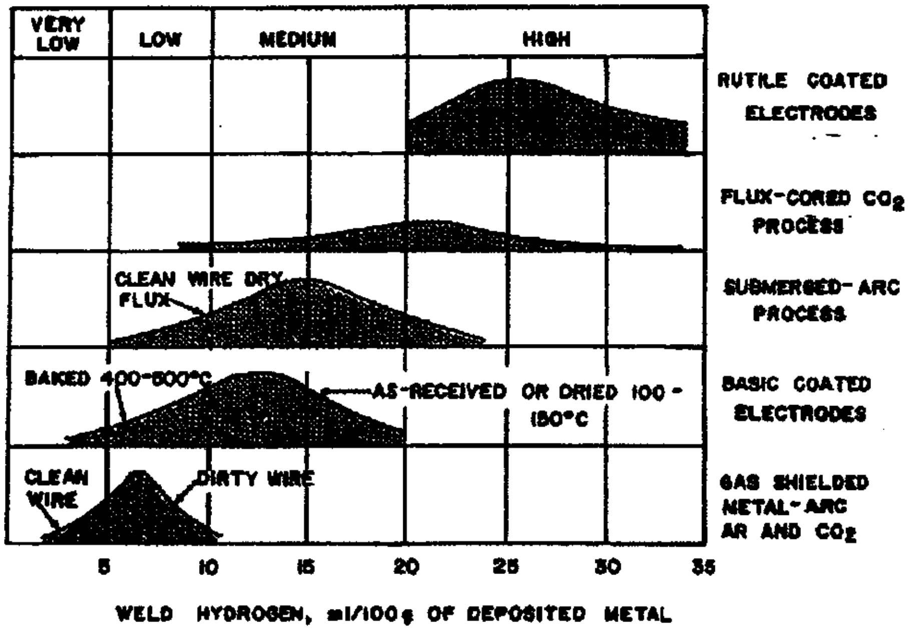
1. hydrogen in the weld metal
2. a crack-sensitive microstructure
3. tensile stress
4. temperatures below 200 C

Causes of HIC

1- Sources of Hydrogen

- Hydrogen comes from
  - hydrogenated compounds in electrode coverings and fluxes
    - Rutile and cellulosic fluxes contain organics and water, and produce weld metal high in hydrogen
    - Basic electrodes are all-mineral and can be baked to drive off moisture
  - contamination of joint surfaces with grease, paint, etc.
  - poor gas shielding or contamination of shielding gases with water vapour and hydrogen

Hydrogen content resulting from various welding processes



Graville, B: The Principles of Cold Cracking Control in Welds, Dominion Bridge Company, Montreal, 1975.

Causes of HIC

2- Microstructure

- The most susceptible microstructure is high-carbon martensite in the coarse-grained HAZ
- HAZs with hardness below 300 Hv have a low susceptibility to cracking
- The risk is significant above 350 Hv.

Causes of HIC

3-Stress

- The stress that acts as the driving force for HIC in-most instances is the residual stress from welding.
- The level of residual stress depends on
  - the yield strength of the material
  - the degree of restraint
- HIC is more probable in high-strength materials or when welding highly restrained joints

Causes of HIC

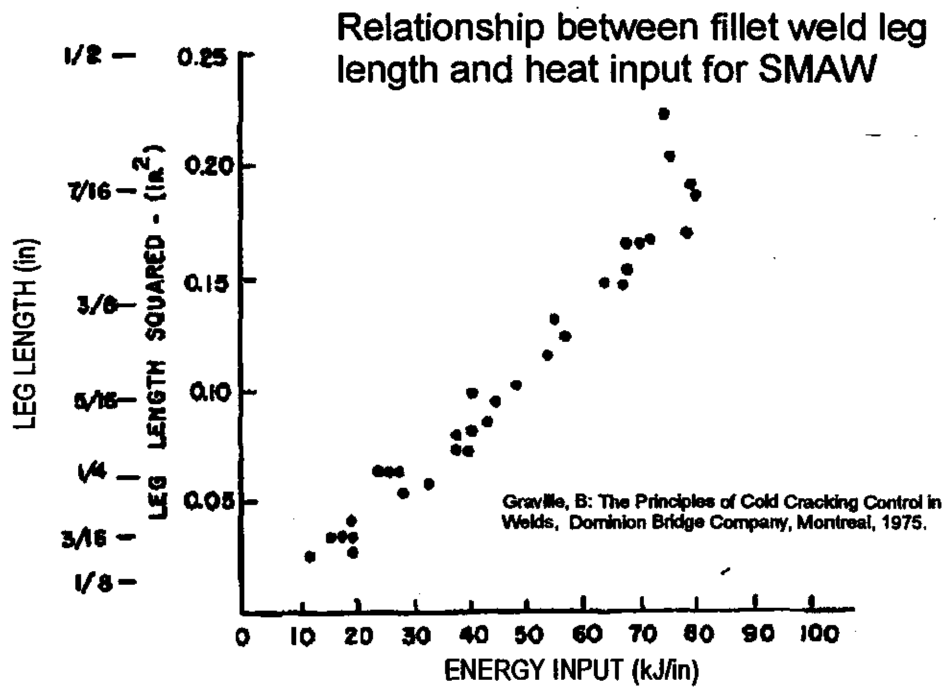
4- Temperature

- Hydrogen is absorbed into the weld metal at high temperatures
- Hydrogen solubility in iron decreases on cooling to ambient temperature
- Hence hydrogen tends to diffuse from the weld to the HAZ after welding
- Cracking may appear days or even longer after welding

HIC-Avoidance

- Use low-hydrogen welding processes
  - baked basic electrodes or fluxes
  - gas shielded processes (GMAW, GTAW or PAW)
  - ensure cleanliness and freedom from contaminants
- control steel composition
  - carbon equivalent < 0.45
- reduce cooling rates and peak HAZ hardness (dependent on thickness and CE)
  - preheat joint
  - minimum heat input, bead area or fillet weld size
- minimise joint restraint

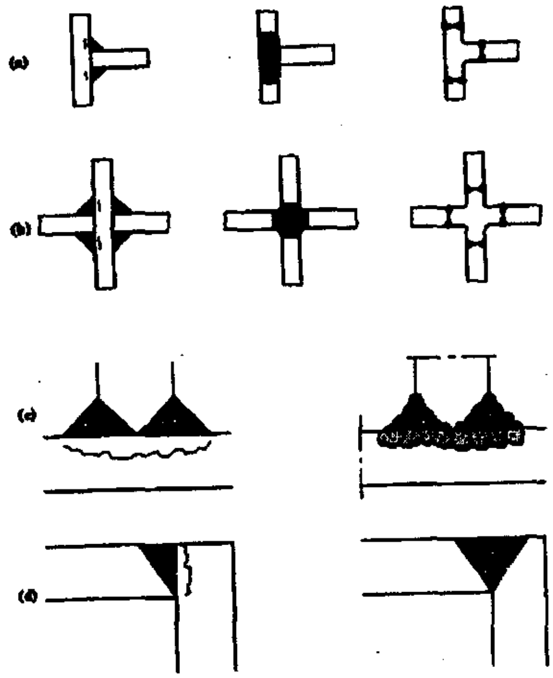
HIC-Avoidance



Lamellar Tearing

- Lamellar tearing occurs in the base metal due to the combination of high local stress and low ductility in the through-thickness direction
- It is associated with welds on thick sections where the weld boundary is approximately parallel to the plate surface.
- The cracking is near the weld boundary and lies mostly parallel to the surface of the plate

Lamellar Tearing--Avoidance



(a) & (b) replace fillets with solid weld metal or forgings

(c) "buttering" with ductile weld metal

(d) corner joint redesign

Reheat Cracking

- Reheat cracking occurs in the HAZ of alloy steels during PWHT
  - Results from strengthening by precipitation within the HAZ grains. Concentrates deformation at the grain boundaries
- Cracks are intergranular and follow the prior austenite grain boundaries
- Contributing factors are
  - a susceptible alloy composition
  - a susceptible HAZ microstructure
  - a high level of residual strain
  - temperature in the strain relaxation range
- Not usually a problem with C-Mn or HSLA steels.

Reheat Cracking-Avoidance

- Material selection
  - Limit carbide formers (V)
- Minimize restraint
- Rapid heating to stress-relief temperature to minimize precipitation
- Non-destructive examination after PWHT

Porosity

- Porosity in weld metal is formed by entrapment of gas evolved during solidification.
- In steels, the gases that participate in porosity formation are CO from reaction of oxygen with carbon in the steel, H_2, N_2, and H_2S.
- Excessive porosity is avoided by
  - proper welding conditions,
  - cleanliness of the joint surfaces and consumables
  - deoxidizers such as Al, Ti or Si added to the welding filler.

Inclusions

- Large non-metallic inclusions in steel are of two types.
- The first is slag entrapped because it was not removed from a previous weld or entrained by improper welding technique
- Inclusions can also be generated by foreign materials entering the weld pool, especially pieces of melted tungsten electrode in GTAW or copper guide tubes in GMAW and SAW.