# Lecture 7:
# Weldability and Structural Steels

MMat 380

## Lecture outline

- Carbon equivalent and weldability
- Impact properties
- Structural steels (A36 specification)

# Weldability

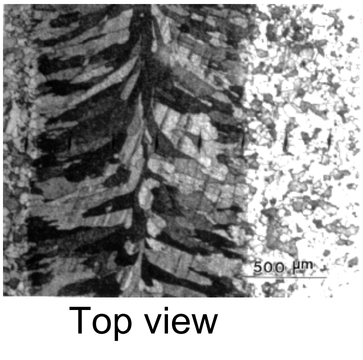
- Carbon Equivalent:

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

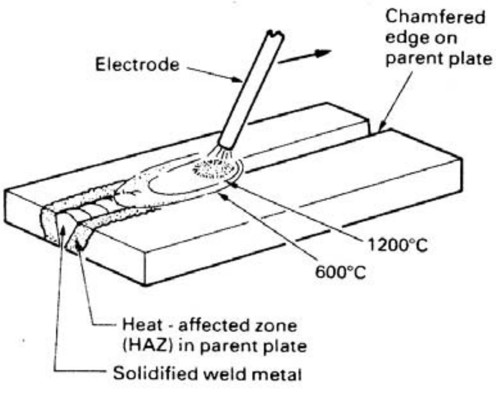
| C.E. | Weldability | Procedure |
|---|---|---|
| <0.4 | Excellent | Preheat to remove moisture |
| 0.41-0.45 | Good | Preheat + low H electrode |
| 0.46-0.52 | Fair | Preheat + low H elec. + interpass T control |
| >0.52 | Poor | Preheat + low H elec. + interpass T control + post weld heat treatment |

---

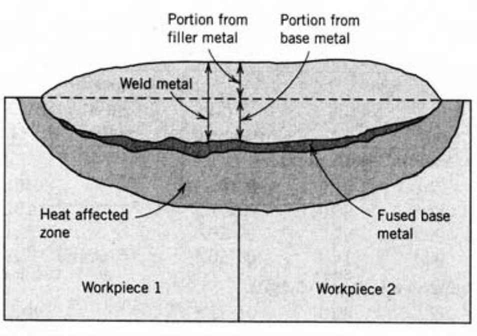
# Typical Weld

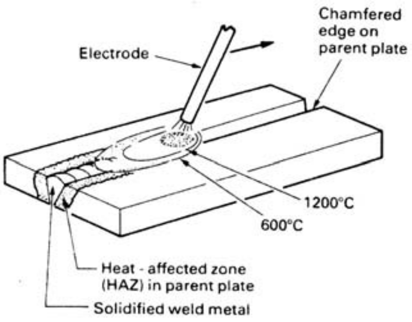


Top view



# Typical Weld





X-sectional view

---

# Welding of steels

Must consider 5 characteristics:

- Possible martensite formation in HAZ
  - chemistry and cooling rate
- Presence of H
  - from rods and moisture preheat: allows H to diffuse out
- Residual stresses/joint restraint
- Weld strength and need to preheat
- Match corrosion characteristics

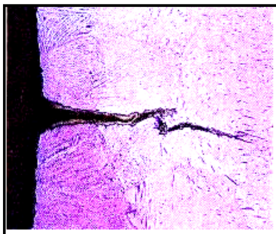
# Martensite in HAZ

- Could form martensite and crack if:
  - Cooling Rate (CR) > Critical CR
  - Large section sizes
  - Increased alloy content
- Critical Cooling Rate (CCR) depends on steel chemistry
  - Don’t want high alloyed steel
  - Don’t want fast cooling rates after welding

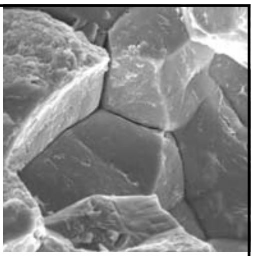
---

# Martensite in HAZ

- Actual CR in HAZ depends on:
  - Ambient temperature
  - Part size
- So you trade off more danger of martensite formation for:
  - higher alloy steel for strength or corrosion resistance (then you have a lower CCR)
  - welding larger section size or in a cold climate



# Presence of H



H **embrittles** welded area

especially if martensite is present in HAZ and joint is restrained

- H migrates to areas of high triaxial stress (i.e. martensite)
- H forms by:
  - Breakdown of moisture in the arc
  - Some flux components liberate H in the arc

---

# Presence of H

- If critical:
  - Specify low H rod (flux won't breakdown)
  - Keep rods dry
  - Preheat: slow cooling rate (H diffuses out) and lower stresses
- But low H rod lowers productivity and not as good looking weld bead

# Residual stresses/joint restraint

- Care in production set-up to minimize stresses during welding or get:
  - centre-line cracking
  - early fatigue failure
- High residual stresses always associated with welding so:
  - May have to stress relieve (pressure vessels etc.)

---

# Weld Strength

- Rod or wire filler metal must match parent metal for strength, toughness etc.
- increasing C.E. increases strength
- If C.E.>0.4 must preheat
  - Can specify a maximum C.E.

# Guidelines

- If C.E.< 0.4 – need not preheat
  - Except: in cold climes or for heavy sections
- If C.E. > 0.4 – must preheat
  - Preheat area to be welded to slow cooling rate so that it is less than CCR
  - C is the most important element in C.E. eq.
- As **C increases**, any martensite which forms will be **harder** and more **brittle**

---

# Need to preheat when

- Increased chemistry (C.E.)
- Increased joint restraint
- Increased section size
- To eliminate or reduce H cracking
- Decreased ambient temperature

# Impact Testing

- Basic Charpy test: ASTM Standards

$$K_{1c} = Y\sigma\sqrt{\pi a}$$

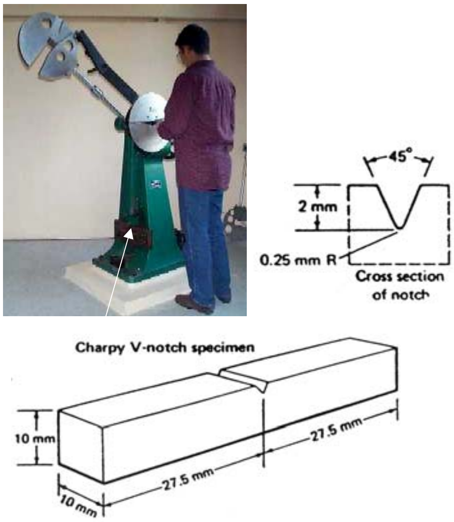
Y = dimensionless parameter

a = crack length

σ = loading/stress condition

K = stress intensity factor (magnitude of crack tip stress field)

Plain strain if thickness B ≥2.5



---

# Relating Charpy test results to $K_{1C}$

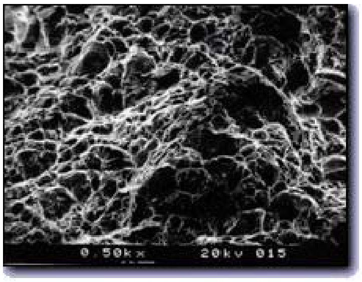
- As $\sigma_y$ increases, B decreases and have brittle failure at thinner sections
- Empirical relationship: Jones

$$K_{1c}=(CVN)^{1/2}$$

  - From ship industry: need ~20J at lowest temperature to avoid brittle failure

## Types of failure

- Ductile: grey, fibrous with distortion



- Brittle: cleavage, crystalline, no distortion

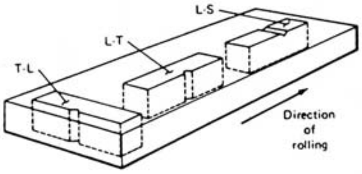
---

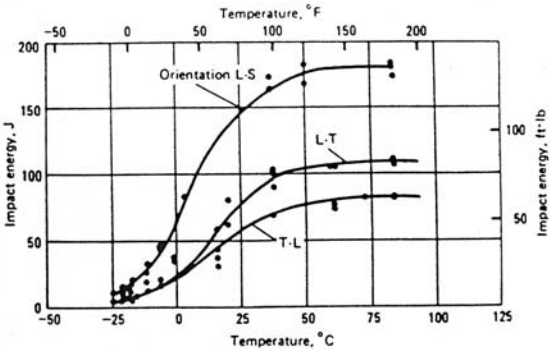
## Factors affecting toughness

- Orientation of sample vs. rolling direction
- Chemical content %C, %Mn
- Finishing temperature

# Anisotropy of toughness

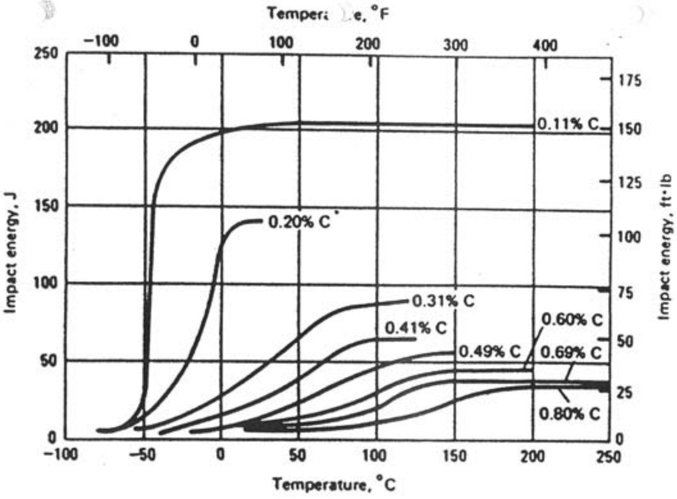
- Anisotropy: property differs by orientation of sample





---

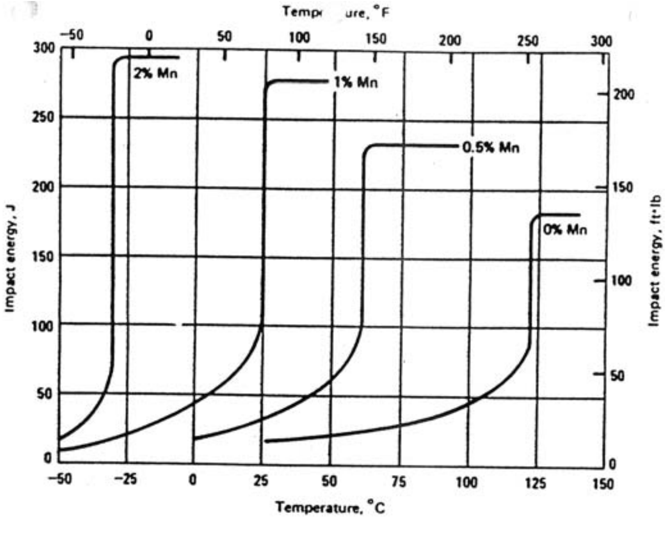
# Effect of C content on toughness



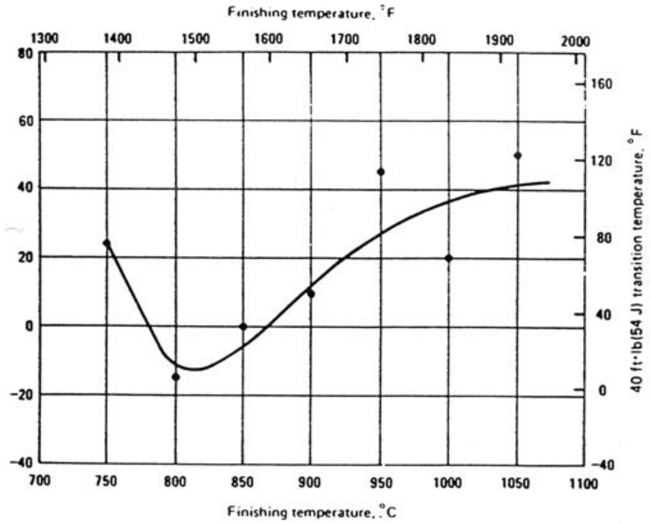
# Effect of C on toughness of steel

| %C | 25J transition temp. (°C) | Upper shelf energy (J) |
|---|---|---|
| 0.11 | -50 | 205 |
| 0.20 | -35 | 140 |
| 0.41 | 25 | 65 |
| 0.80 | 150 | 35 |

# Effect of Mn content on toughness



# Effect of finishing temperature on toughness



---

# Structural steels (C-Mn)

- mild steels (C<0.25%) used for the last 50-60 years
- provided in the hot rolled condition (plate, beams etc)

- **Finish hot rolling @ 900-1000°C**
- ASTM standard A36; CSA Standard 44W – (300W)

| %C | %Mn | YS (MPa) | UTS (MPa) | % elongation |
|---|---|---|---|---|
| 0.15-0.25 | 0.6-1.2 | 200-500 | 400-500 | 25 |

# Alloying: trends for structural steels

| Condition | Resistance to brittle fracture | Weldability | Strength |
|---|---|---|---|
| Increased %C | Decreases | Decreases | Increases |
| Increased %Mn | Increases | Decreases | Increases |
| Decreased grain size | Increases | ---------- | Increases |

# Changes in steel chemistry

| Parameter | Traditional | High Strength |
|---|---|---|
| %C | 0.2-0.25 | 0.06-0.15 |
| %Mn | 0.8-1.2 | 1.2-1.5 |
| Microalloy additions | ------ | Nb/V (<1%) |
| Grain size (ASTM #) | 6 | 12 |
| C.E. | 0.38 (0.33-0.45) | 0.33 (0.26-0.40) |

## Important relationship:

- Take C out of structural steel to:
  - Increase toughness at shelf energy
  - Decrease ductile to brittle transition temperature
- Compromise: toughness vs. strength
- Take C out – must increase Mn or decrease grain size to compensate for loss in strength

---

## ASTM A 36 Specification for Structural Steel

Discussion

Notch toughness

Corrosion Resistance

Weldability

Gas Cutting

Formability

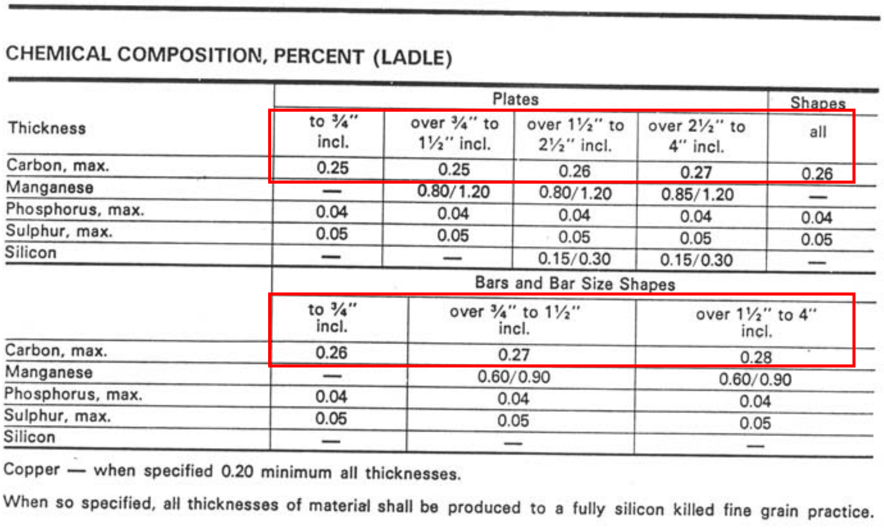
Chemical composition

Mechanical properties

Typical engineering properties

Suggested welding practices

# Zoom in on Section of ASTM A 36



CHEMICAL COMPOSITION, PERCENT (LADLE)

| | Plates | | | | Shapes |
|---|---|---|---|---|---|
| Thickness | to ¾" incl. | over ¾" to 1½" incl. | over 1½" to 2½" incl. | over 2½" to 4" incl. | all |
| Carbon, max. | 0.25 | 0.25 | 0.26 | 0.27 | 0.26 |
| Manganese | — | 0.80/1.20 | 0.80/1.20 | 0.85/1.20 | — |
| Phosphorus, max. | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Sulphur, max. | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Silicon | — | — | 0.15/0.30 | 0.15/0.30 | — |

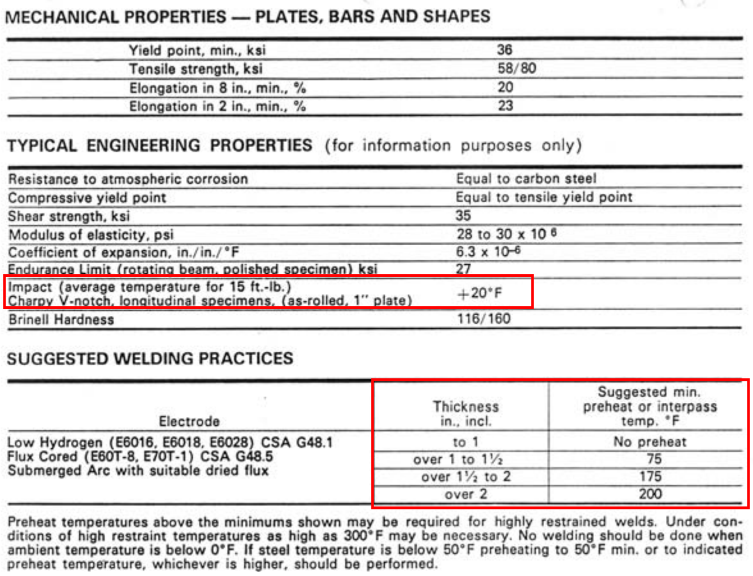
| | Bars and Bar Size Shapes | | |
|---|---|---|---|
| | to ¾" incl. | over ¾" to 1½" incl. | over 1½" to 4" incl. |
| Carbon, max. | 0.26 | 0.27 | 0.28 |
| Manganese | — | 0.60/0.90 | 0.60/0.90 |
| Phosphorus, max. | 0.04 | 0.04 | 0.04 |
| Sulphur, max. | 0.05 | 0.05 | 0.05 |
| Silicon | — | — | — |

Copper — when specified 0.20 minimum all thicknesses.

When so specified, all thicknesses of material shall be produced to a fully silicon killed fine grain practice.

---

# Zoom in on Section of ASTM A 36



MECHANICAL PROPERTIES — PLATES, BARS AND SHAPES

| | |
|---|---|
| Yield point, min., ksi | 36 |
| Tensile strength, ksi | 58/80 |
| Elongation in 8 in., min., % | 20 |
| Elongation in 2 in., min., % | 23 |

TYPICAL ENGINEERING PROPERTIES (for information purposes only)

| | |
|---|---|
| Resistance to atmospheric corrosion | Equal to carbon steel |
| Compressive yield point | Equal to tensile yield point |
| Shear strength, ksi | 35 |
| Modulus of elasticity, psi | 28 to 30 x $10^6$ |
| Coefficient of expansion, in./in./°F | 6.3 x $10^{-6}$ |
| Endurance Limit (rotating beam, polished specimen) ksi | 27 |
| Impact (average temperature for 15 ft.-lb.) Charpy V-notch, longitudinal specimens, (as-rolled, 1" plate) | +20°F |
| Brinell Hardness | 116/160 |

SUGGESTED WELDING PRACTICES

| Electrode | Thickness in., incl. | Suggested min. preheat or interpass temp. °F |
|---|---|---|
| Low Hydrogen (E6016, E6018, E6028) CSA G48.1<br>Flux Cored (E60T-8, E70T-1) CSA G48.5<br>Submerged Arc with suitable dried flux | to 1 | No preheat |
| | over 1 to 1½ | 75 |
| | over 1½ to 2 | 175 |
| | over 2 | 200 |

Preheat temperatures above the minimums shown may be required for highly restrained welds. Under conditions of high restraint temperatures as high as 300°F may be necessary. No welding should be done when ambient temperature is below 0°F. If steel temperature is below 50°F preheating to 50°F min. or to indicated preheat temperature, whichever is higher, should be performed.

# Questions on A 36 Specification

1) Why does the maximum carbon increase as the plate thickness or bar diameter increase?

2) Why is a preheat suggesting during welding for plate thicknesses over 1 inch? Why does this preheat temp. Increase as the thickness increase

3) Why is a Si level specified for plates over 1.5 inches?

4) Why is the value for the Impact Charpy V-notch specimens given as an average temperature?

---

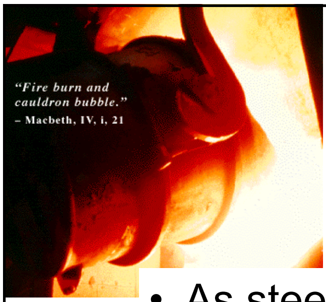
# A36 – Structural Steel Specification

- Increased allowance for $C_{max}$ with increased section size
  - to compensate for lower strength from larger $\alpha$–grain size
- No Mn specs for small section sizes
  - don't have to worry about weldability for small sizes
- Si levels – need killed steels for thicker sections
  - better DBTT with killing
  - offsets larger $\alpha$-grain size effect

# A36 – Structural Steel Specification

- Endurance limit: 186 MPa = ~40% UTS
- Charpy V notch – avg T for 15 ft-lb = -7$^{o}$C
  - Longitudinal specimens transverse direction
  - Best results as rolled 1” plate
- Welding:
  - Low H rod
  - No preheat small sections
  - Up to 93$^{o}$C for over 2” (but high restraint my need 150$^{o}$C)
  - No welding when ambient T < -18$^{o}$C (0°F)
  - Steel T must be at least 10$^{o}$C

---



# Steel solidification

- As steel cools and solidifies, solubility of O in steel decreases
  - if left to itself it will bubble out **violently** during casting; the steel will look “alive”
  - If instead Al or Si is present it will bind the oxygen and carry it to the slag layer calmly, steel will look “killed”

# Steel production

- Rimmed ingot structure
  - Reaction of dissolved O and C to form CO and $CO_2$ until a heavy **rim** of relatively pure iron, free of voids is produced
- Semi-killed ingot structure
  - Only a slight amount of gas is allowed to evolve during solidification
- Killed ingot structure
  - Fully killed steels evolve no gas and form a pipe cavity at the top of the into (Al, Si act as deoxidizers and stop gas reaction)

---

# Steel alloys

Extremely wide range of properties and applications of steel can be addressed as:

- Plain carbon steels
- Low alloy steels
- Alloy steels

# Plain carbon steels

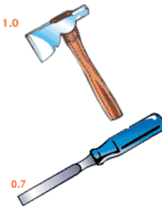
- Equilibrium hot rolled or cold drawn
- Low C (%C <0.1)
  - High stiffness, good toughness, weldability, deformability, low cost
  - Automotive and appliances

- Structural steels (0.1<%C<0.22)
  - High stiffness, good toughness, weldability, low cost
  - Structural forms: beams, girders, columns

---

# Plain carbon steels

- Intermediate C (0.3<%C<0.6)
  - Increasing strength and wear resistance but decreasing toughness and weldability
  - Inexpensive, shallow hardening machine parts
- High C (0.6<%C<1.05)
  - Increasing hardenability, strength, hardness and wear resistance
  - Decreasing toughness, poor weldability
  - Inexpensive cutting, forming, shaping tools



# Why alloy steel further?

- Plain carbon steels have the following limitations:
  - Cannot be strengthed to >690 MPa without significant loss in toughness and ductility
  - Large sections cannot be made with a martensitic structure throughout: not deep-hardenable
  - Rapid quench rates are necessary for full hardening: shape distortion and cracking
  - Poor impact resistance at low temperatures
  - Poor corrosion resistance
  - Oxidizes readily @ higher temperatures

---

# Alloy steels

- Purpose of adding alloying elements to plain carbon steels:
  - Improve mechanical properties by increasing **depth** to which steel can be hardened with decreasing quench severity (water, oil…)
  - Allows higher tempering temperatures while maintaining high strength **and** high ductility
  - Machine, automotive and truck drive suspension components

# Alloy steels

- 0.2<%C<0.6 – medium C steels
- All are heat treatable
- Can heat treat lower %C than plain carbon steels because alloy additions increase hardenability
- Alloys Cr, Mo, Ni (in order of importance)
  - <3% total additions, usually ~1.5%
- Mn is really the most important alloy **addition** but it is **always** present in steels

---

# Alloy steels: most important series

| **Series** | **additions** |
|---|---|
| 4xxx | Ni, Mo, Cr |
| 5xxx | Cr 0.8-1.45 |
| 87xx | Ni – 0.55, Cr - 0.50, Mo – 0.25 |
| 86xx | Ni – 0.55, Cr - 0.50, Mo – 0.20 |
| 15xx | Mn – 1.30 |
| 13xx | Mn – 1.75 |