Welding Metallurgy

Distortion
Residual Stress
&
Post-Weld Heat Treatment

Lecture Scope

- Typical patterns of distortion & residual stress in welded assemblies
- Effects of residual stress
- Methods for prevention and correction of distortion
- Heat treatment of steel weldments

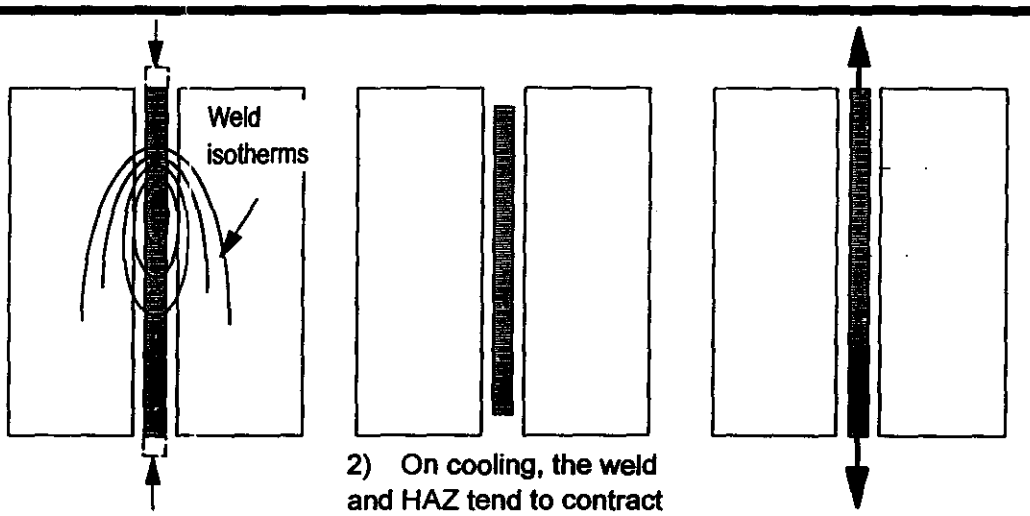
Residual Stress: Definitions

- Residual stresses are the stresses that exist in a structure in the absence of external loads
- Residual stresses can be produced in metal structures by many processes including: casting, heat treatment, forming and bending, and thermal cutting.
- Welding produces residual stress and distortion as a result of localised heating and cooling of the work material

Causes of Residual stress

- During welding, the weld and HAZ are heated to temperatures well above those of the surrounding material
- The weld and HAZ deform plastically because their thermal expansion is resisted by the surrounding material
- As the weld cools and contracts, tensile stresses develop elastically
- Welds contain tensile stresses that approach the yield stress.

Weld Thermal Strains



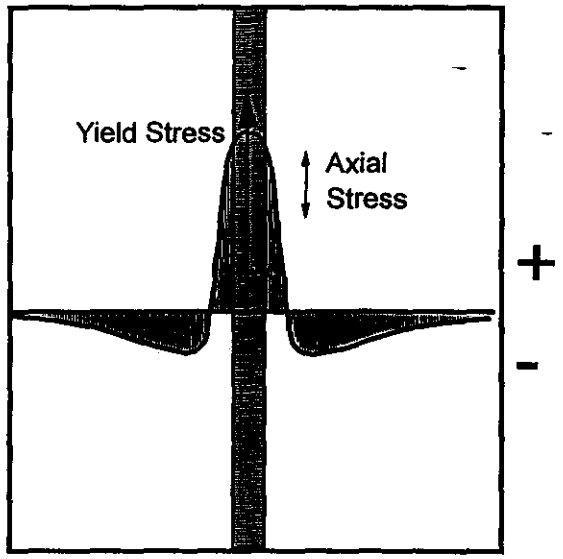
1) On heating, the thermal strains are resisted by the surrounding material, causing plastic deformation

2) On cooling, the weld and HAZ tend to contract

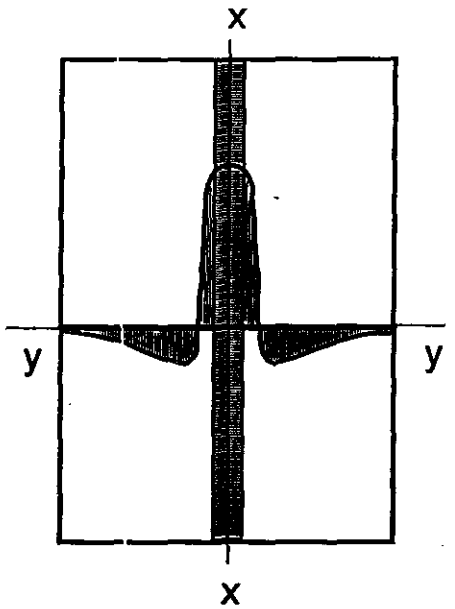
3) The contraction is again resisted by the surrounding material, leaving the weld and HAZ in a state of tension

Axial Residual Stress Pattern

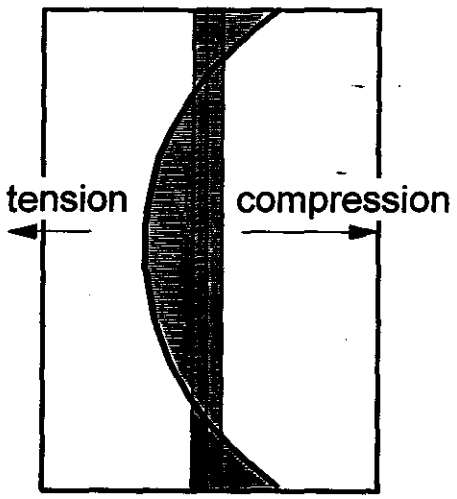
The tensile stress in the weld is balanced by compressive stresses of lower magnitude in the surrounding plate



Transverse Stresses in Butt Joint

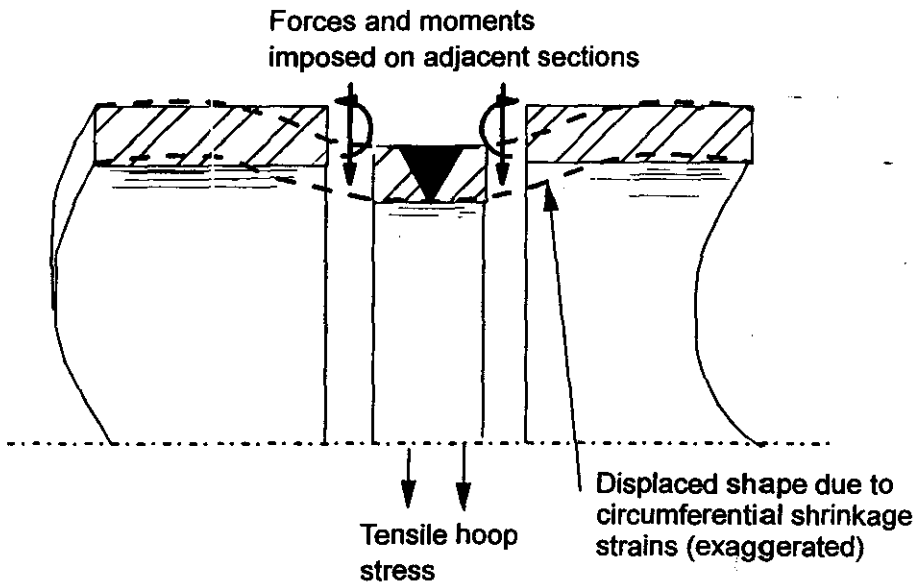


Axial stress



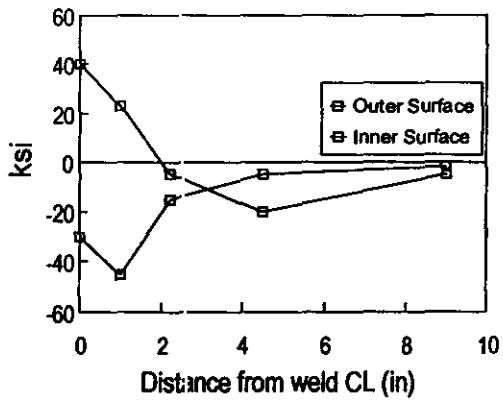
Distribution of y-stress component along x-x

Pipe Girth Weld Displacements

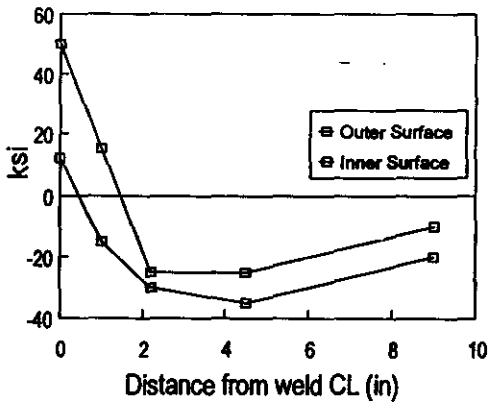


Typical Pipe Girth Weld Stresses

Longitudinal Stresses



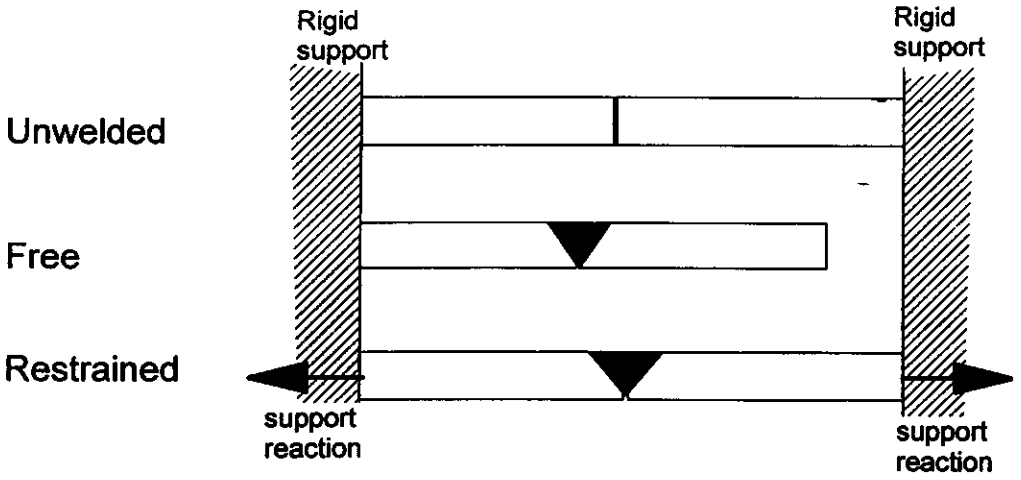
Circumferential Stresses



Restraint Stresses

- When the workpiece is free to expand or contract, residual stresses are confined to the region of the weld
- When the workpiece is restrained, e.g. between rigid anchors, long-range reaction stresses develop

Restraint Stresses



Examples:

- a short run of pipe welded between a rigidly mounted pump and a vessel
- a beam welded between two stiff columns

Effects of Residual Stress

- Residual stresses do not affect the load carrying capacity of ductile materials that fail by yielding
- Residual stresses may promote failure mechanisms that are sensitive to localized stresses
  - fatigue
  - brittle fracture
  - stress corrosion cracking
  - creep cracking

Control of Residual Stress

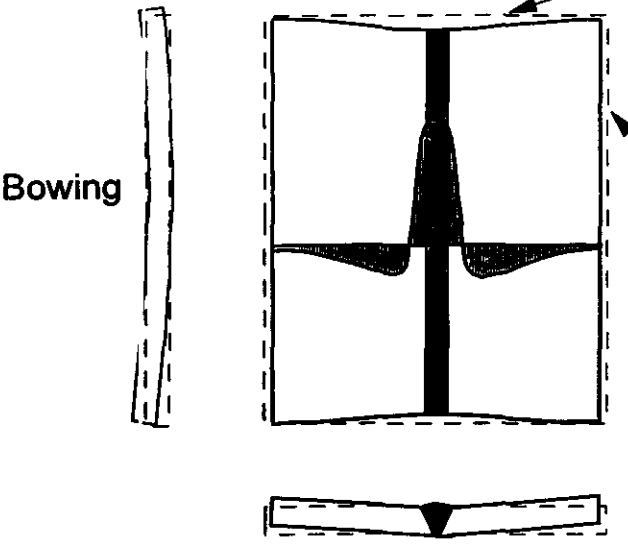
- Use minimum required weld size and heat input
  - J or U preparations give smaller weld areas
- Minimise constraint during welding
- Stress relief
  - Heat treatment
  - Mechanical e.g. vibratory

Distortion

- Distortion in welded fabrications is caused by movements to accommodate thermal stresses
- Distortion in welded fabrications consists of:
  - transverse shrinkage
  - longitudinal shrinkage
  - angular rotations
- Distortion is a problem mostly with thinner materials

Butt Weld

Typical distortion pattern (exaggerated)

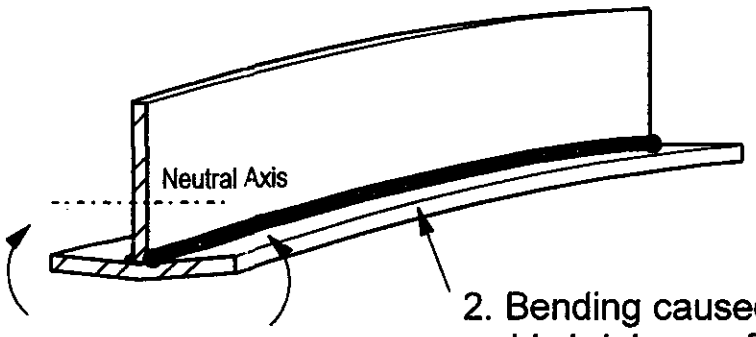


Axial Shrinkage ~0.1% of length

Transverse Shrinkage ~1.5-3 mm

Angular Rotation ~1-3°

Fillet Weld Distortion



1. Angular Rotation

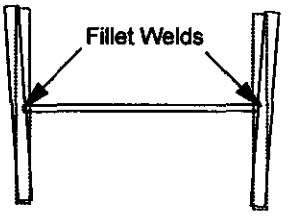
2. Bending caused by weld shrinkage offset from neutral axis of section

Peaking of Stiffened Panel

Examples: bridge deck, ship hull

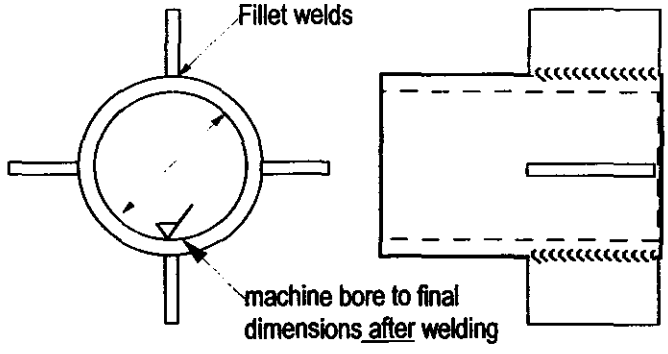
Control of distortion -1

1. Minimise heat input
   - Maximise melting efficiency, i.e. welding processes with high energy density
2. Use minimum required weld sizes,
   - e.g. intermittent rather than continuous fillet welds, J or U preparations
3. Balance welds about neutral axis
   - e.g. double V preparation, simultaneously weld top and bottom of plate girder
4. Use clamps, jigs & fixtures
5. Preset the workpiece to compensate for anticipated changes, for instance:



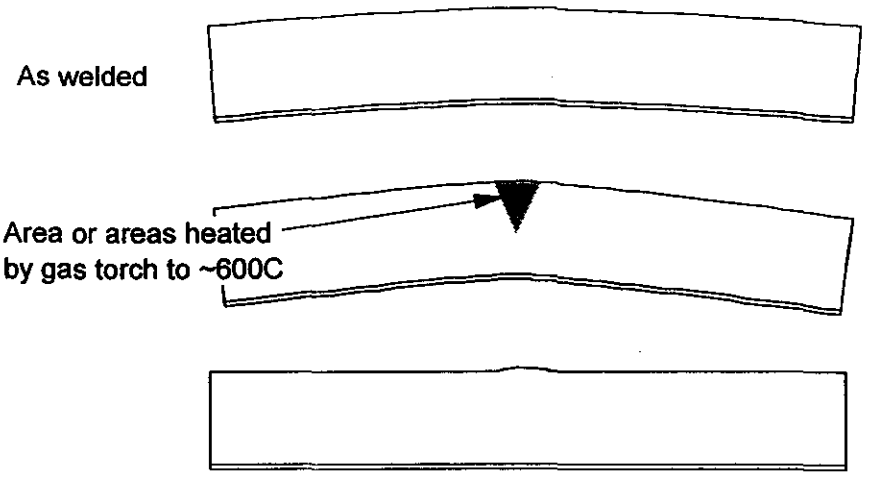
Control of distortion -2

- Avoid using welding for precision assembly
- Machine to final dimensions after welding



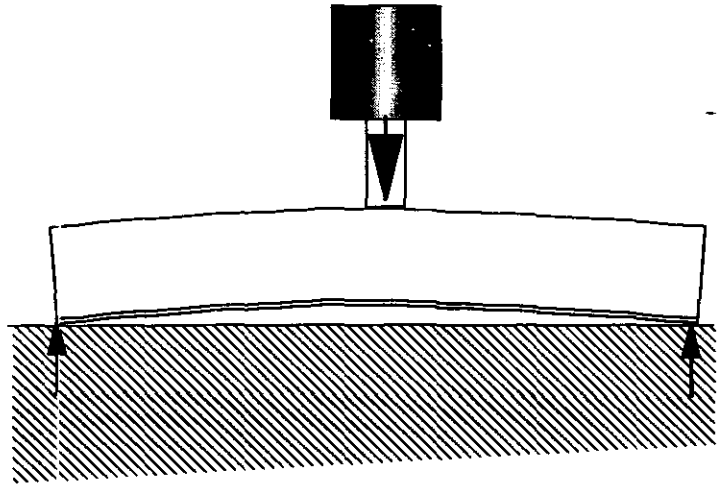
Correction of distortion -1

- Flame Straightening



Correction of distortion -2

- Mechanical straightening



Heat Treatment of Welds

- Heat treatment is costly and should be avoided unless necessary for satisfactory performance
- May be required by applicable codes and standards

Weld Heat Treatments

- Preheating
  - Heating prior to welding, usually to temperatures less than 200C
  - Applied in welding C-Mn steels to decrease cooling rates and reduce HAZ hardness
  - Not generally required for stainless steels. nickel alloys, titanium zirconium or aluminum
- Post Weld Heat Treatment
  - Heating after welding to relieve stresses, refine weld grain structure, or improve weld properties

Post Weld Heat Treatment

- Definitions
  - Stress Relief
    - Heating to a temperature (usually around 600C) at which the yield strength is reduced such that residual stresses are relieved
  - Normalizing
    - Heating to above the temperature for transformation to austenite (A3) and slow cooling for to refine and homogenize the grain structure
  - Quenching
    - Heating as in normalizing and rapid cooling in water, brine or air to develop high strength.

Post Weld Heat Treatment

- Definitions (cont'd)
  - Tempering
    - Reheating after quenching to below the transformation temperature to reduce hardness and improve ductility
  - Solution Treating
    - Heating to take into solution elements which will be precipitated later in a controlled manner to produce the desired properties
  - Ageing
    - Reheating after solution treating to allow formation of precipitates which strengthen the material.

PWHT Methods

- Furnace Heating
  - Gas or electric most common
  - Restricted to parts that can be contained in a furnace
  - Optimum efficiency and control
- Local Heating
  - Gas burners or electric resistance heaters most common
  - Mostly limited to relatively simple treatments, typically stress relief of steel weldments
  - Main advantage is capability to treat large or immovable structures at low cost.

PWHT Effects on Steels

- ***Stress relief*** reduces residual stress and tempers hardened heat affected zones. In most grades of steel (but not all) it improves ductility and toughness.
- ***Normalizing*** is used to refine the grain structure resulting from welding when optimum properties are required, e.g. electroslag welded pressure vessels
- ***Quench & Temper*** Some steels require Q&T treatments to develop high strength. Sometimes such steels can be welded as-quenched followed by a combined temper/stress relief treatment.
- The metallurgical aspects of welding Q&T steels must be carefully assessed.