Welding Electrodes classifications

welding Filler Metal Designation:-

Carbon steel Electrodes:

The carbon steel Electrodes are designated as

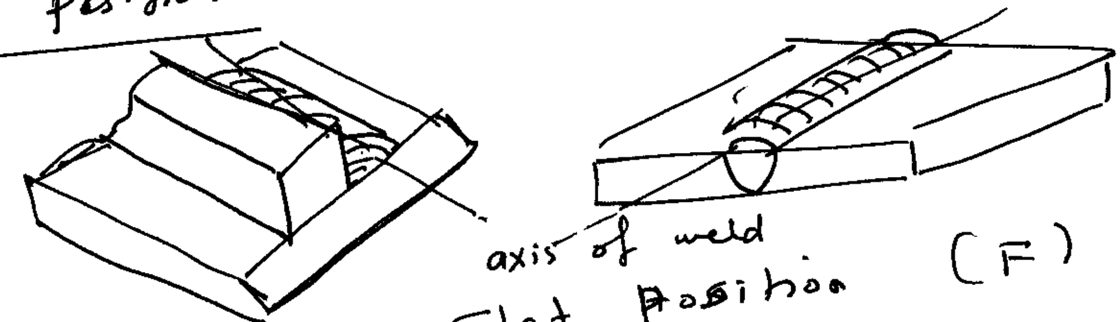
E XX X_1 X_2 — 1 - HZ - R
Mandatory classification Designators

where : E designates an Electrode.
XX : Designated the minimum tensile strength in ksi of the as-deposited weld Metal.
X_1 : Designates the welding position
X_2 : Designates the type of coating and the type of Current for which the electrodes are suitable.

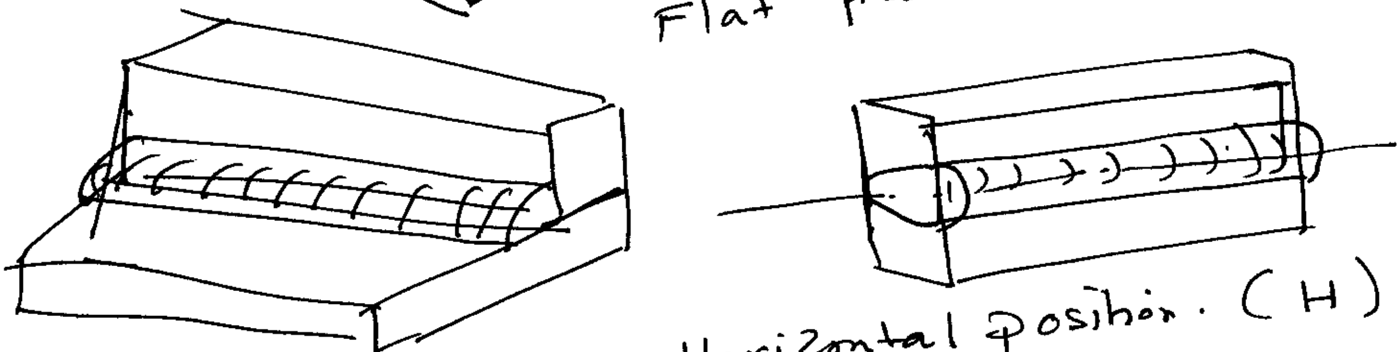
and optional supplemental Designators:
1 : designated that the electrode meets requirements for improved toughness and ductility -
HZ : Designates that the electrode meets the requirements of the diffusible hydrogen test. with an average value not exceeding Z mole of H_2 / 100 grams of deposited metal.
R - Designates that the electrode meets the requirements of absorbed moisture.

welding positions :
1 - Flat, Horizontal, vertical up, overheat (all positions).
2 - Flat, horizontal
4 : Flat, Horizontal, overhead, vertical down.

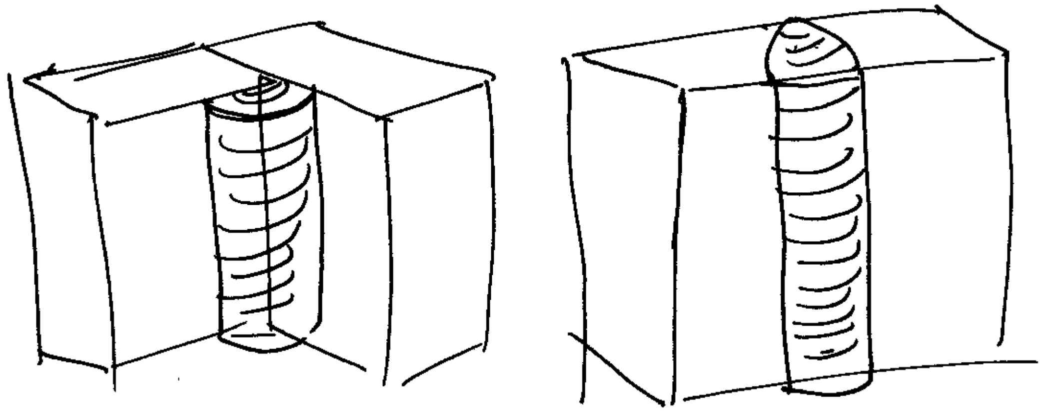
weld positions



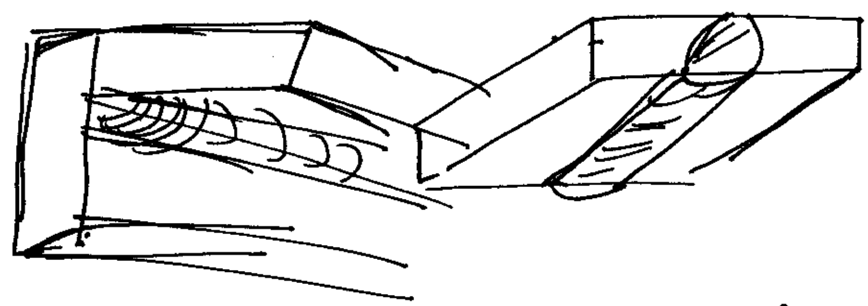
Flat position (F)



Horizontal position. (H)



vertical position (V)



overhead position (OH)

Electrode coverings are classified to 10 designators:

EXX X, 0 — Cellulose, Sodium
1 — cellulose potassium.
2 — Rutile, sodium
3 — Rutile, Potassium.
4 — Rutile iron powder.
5 — Low hydrogen, sodium
6 — Low hydrogen potassium.
7 — Iron powder, iron oxide.
8 — Low hydrogen, iron Powder
9 — Iron oxide, Rutile potassium.

Generally, electrode coating for mild steel and low alloy steels may have from 6 — 12 ingredients, such as:

the electrode coating is designated to provide as many as possible of the following desirable charactristics:

1. specific composition of the deposited weld metal.
2- specific mechanical properties of the deposited weld metal.
3- Elimination of weld metal porosity.
4- Elimination of weld metal cracking.
5 - Desirable weld deposite contour.
6 - Desirable weld surface finish.
7 - Eliminate the under cut adjacent to the weld.
8 - Minimum spatter adjacent to the weld.
9 - Ease of manipulation to control slag in all positions.
10 - stable arc welding.
11 - Penetration control (deep or shallow).
12 - High rate of Metal deposition.
13 - Elimination of Harmful fumes.
14 - Reduces electrode overheating during use.

15 - Strong, tough, durable coating.
16 - Easy slag removal.

Note that
* No single Electrode type will meet all of these Requirements. *

* In stead, there is a variety of electrode types, each having certain desirable charactristics*

Generally the ingredients are such as:

1. Cellulose: Mainly contains cellulases such as vegitables. The disintegration of the cellulose cause or produces hydrogen gas.

This type of coating has the following properties

a- Large amount of hydrogen or gas protection.
b- High percentages of H_2.
c- High probability of cold cracking.
d. Deep Penetration and very stable arc.
e - little slag and a coarse weld deposite
f. Suitable for vertical down welding & first pass.

~~g.~~ Due to High percentage of H_2, this
* electrode is not ~~prefer~~ preferred for welding of High strength steel.

* H_2 improves the arc voltage & penetration.

2- <u>Metal Carbonates</u>: Called also basic
The main ingredients are calcium carbonate and flurites.
These materials adjust the basicity of the slag and produces a reducing atomosphere (with the aid of CO).
The main properties of this type of coating are:
The main properties of H_2.

1. Low percentage of ~~cold~~ cold cracking.
2- Good resistance of slow welding.
3- Limited to horizontal slow welding.
4- Low resistance to hot cracking.
5- Medium penetration and high fusion rate.
6- Good Mechanical properties.

3- Titanuim dioxide (TiO_2):
These materials help to form a high fluid but quick freezing slag. It will provide ionization for the arc. These electrodes are used for all positions.
The percentage of H_2 is to high.
The main properties of such electrodes are:

1. Dense & abundant slag.
2- Medium pentration
3- Stable arc.
4- Weak Resistance to hot cracking.
5- Very versatile and generally used.

Fundamentals of welding:

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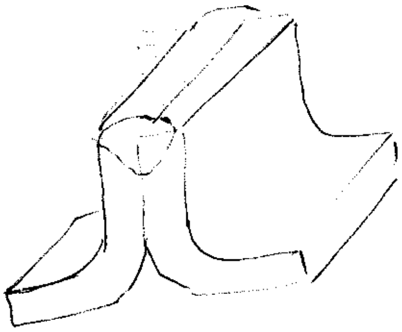
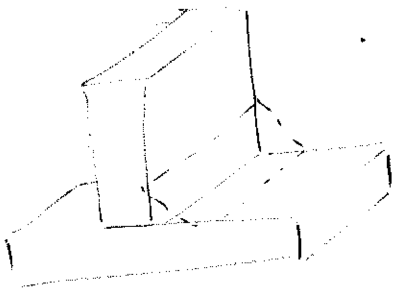
1. welding positions
2. welding joints.

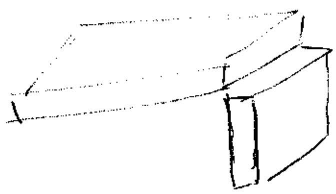
Types of joints:

Lap joint.

Butt joint







Corner joint

T - joint.

Edge joint

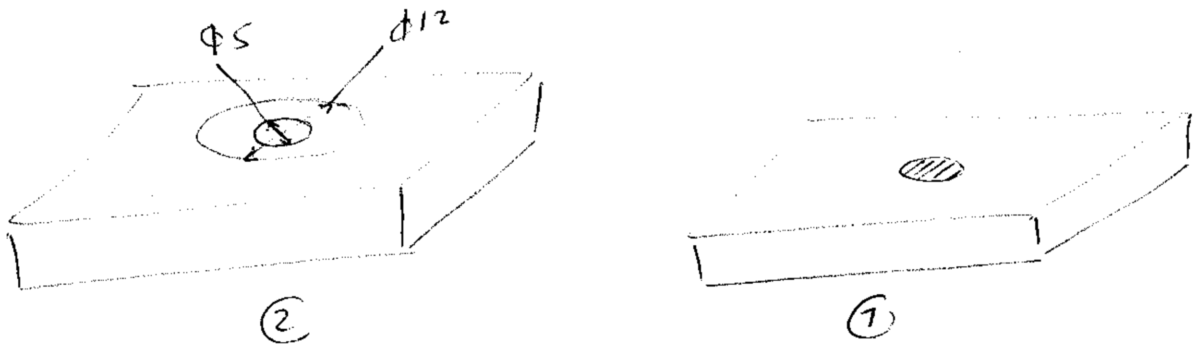
welding power density:-

$$\text{power density} = \frac{\text{Power}}{\text{Area}} = \text{watt}/mm^2$$

welding process	power density w/mm^2
Oxyfuel.	10
Arc welding	50
Resistance welding	1000
Laser beam welding	9000
Electron beam welding	10000

EX: A heat source gives 3000 watt
the heat impinges the surface at a circular point area.

if 70% impinges at 5mm diameter.
and 90% impinges at a concentric area of $\phi = 12$mm
what are the power density of the 5 mm dia.
and 12 mm concentric ring



for 1 $A = \frac{\pi}{4} \times 5 \times 5 = 19.63\ mm^2$

$70\% \times 3000 = 2100$ watt

$\therefore$ power density $= \frac{2100}{19.63} = 107\ watt/mm^2$

for 2 $A = \frac{\pi}{4}(12^2 - 5^2) = \frac{\pi}{4}(144 - 25) = \frac{\pi}{4}(119) = 93.4\ mm^2$

% of power for a $\phi 12$ ring $= 97\% \times 3000 - 70\% \times 3000$
$= 2910 - 2100 = 810$

$\therefore$ Power density $= \frac{810}{93.4} = 8.7\ watt/mm^2$

power density for the inner circle is higher than the ring.

The quantity of heat can be estimated by:

$$U_m = K T_m^2 \quad \text{Joul}/mm^3$$

T_m = Melting point K°

$K = 3300 \times 10^{-6}$ if T is in K° $\quad 3300 \times 10^{-6}$ $Joul/K^\circ mm^3$

the net heat available for welding H_w

$$H_{weld} = f_1 f_2 H = \eta_1 \eta_2 \cdot H$$

H = heat generated for welding.

η_1 = heat transfer efficiency.

η_2 = melting efficiency.

$H_w = U_m \times V$ where V = volume of the melted metal.

HR_w = Rate of heat deliverd Joul/sec

$$HR_w = U_m \cdot A_w \cdot v = \eta_1 \eta_2 HR = U_m WVR$$

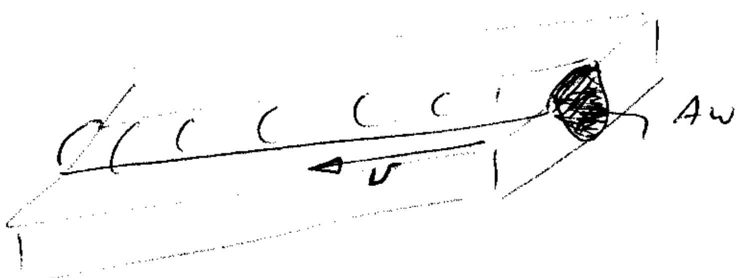
HR = rate of ~~ener~~ input energy generated by power source

WVR = Volume rate of the ~~to~~ metal welded mm^3/sec

$$HR_w = A_w \cdot v \times U_m$$

v = welding speed mm/sec

A_w = welded zone area mm^2



EX:- the power source in a particular welding process with an efficiency $\eta_1 = 0.7$

$T_m = 1760°K$

$\eta_2 = .50$

$A_w = 20\ mm^2$

and it can supplying 3500 watt

$U_m = K T_m^2 = 3300 \times 10^{-6} (1760)^2 = 3.03 \times 3300$

$= 10.3\ J/mm^3$

$H_{wR} = \eta_1 \eta_2 \cdot HR = U_m \cdot A_w \cdot v$

since

$H_w = \eta_1 \cdot \eta_2 \cdot H = U_m A_w \cdot v$

$$\boxed{\therefore v = \frac{\eta_1 \eta_2 \cdot HR}{U_m \cdot A_w}} = 5.95\ mm/sec$$

In gas welding (oxy-acetylene)

Heat generated = volume rate of acetylene × heat libriated during combustion

$= 55 \times 10^6$ Joul/m^3

$HR = m^3/hr \times$ Joul$/m^3$ = Joul/hr

net heat $HR = \eta_1\ HR$

η_1 = heat transfer efficiency =

Power density $= \frac{HR \times \eta_1 \times \eta_2}{A}$ where η_2 = heating efficiency

Power Source in Arc welding:

$$HRw = \eta_1 \eta_2 I . E = U_m . A_w . v$$

10/10 ✓

E = Voltage volt.
I : Current Amp.

EX: A gas Tungsten arc welding process uses 300 Amp. and ~~20~~ 20 volt.
melting efficiency $\eta_2 = 0.5$
$U_m = 10$ joul/mm^3

Find ① - power in welding
② - Rate of generation of heat HRw
③ - VRW of welded metal.

(a) $P = I . E = 300 \times 20 = 6000$ watt.

$\eta_1 = 70\%$ for TIG
$\eta_1 = 90\%$ for MIG

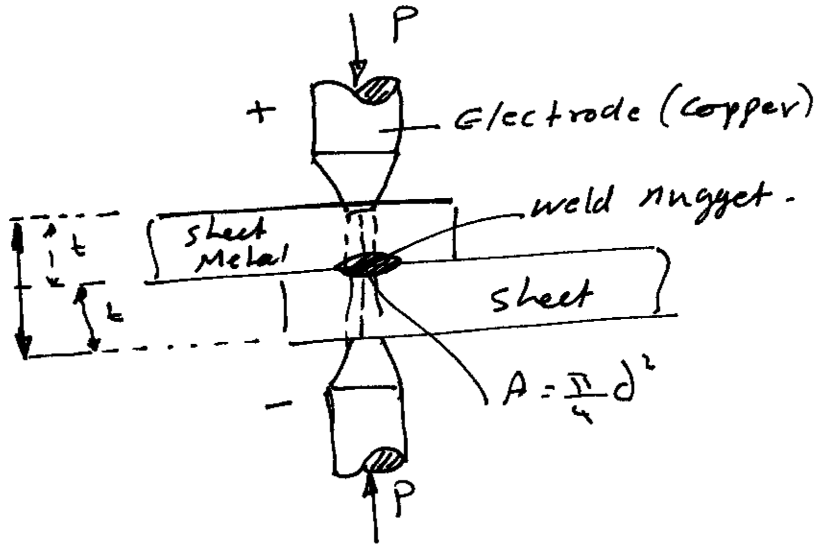
(b) $\therefore HRw = \eta_1 \eta_2 E . I = 0.5 \times 0.7 \times 300 \times 20$
$= 2100$ watt $= 2100$ J/sec

(c) $WVR = U_m / HRw = 10$ J/mm^3 / 2100 J/sec

since
$$WVR = \frac{HRw}{U_m} = \frac{2100}{10} = 210 \text{ mm}^3/\text{sec}$$

$$HRw = U_m . WVR$$

Resistance welding



$H = I^2 . R \Delta t$

R = Resistance

$R = \rho \frac{L}{A}$

ρ = specific resistance

L = length of wire

A = Cross sectional area.

$\therefore H = I^2 . R . t = I^2 . \rho \frac{L}{A} \Delta t$

$H. = I^2 . \rho . \frac{2t}{\frac{\pi}{4} d^2} = \frac{8 . I^2 . \rho . t}{\pi . d^2} . \Delta t$

The resistance R of the path from + to - ve electrode consists of :

1. Resistance of the interface between Electrode & sheet surface.
2. resistance of the sheet
3. resistance of the interface between two sheets
4. Electrode resistance.

Ex: A resistance spot welding is used to weld Two sheets of 1.5 mm thick. The current I used is 12000 Amp. The duration is 0.2 sec. diameter of electrode = 6 mm and resistance = 0.0001 Ω and $U_m = 12$ Joul/mm^3

$$H = I^2 \cdot R \cdot t = 12000^2 \cdot \times 0.0001 \times 0.2$$

$$= 2880 \text{ joul}$$

volume of the nugget $= A \cdot h = 2.5 \times \frac{\pi}{4} 6^2$

$= 70.7 \text{ mm}^3$

$H_m = U_m \cdot V$

$H_m = 12 \cdot \times 70.7 = 848$ Joul.

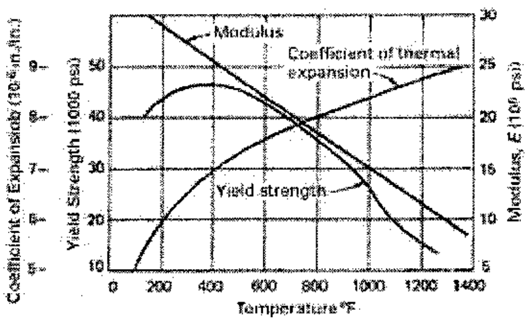
Heat required to melt this nugget.

$\therefore$ $2880 - 848 = 2032$ Joul is absorbed into the Sorounding.

$\therefore$ heat dissipation $= \frac{2032}{2880} = 70.6\%$.

PREVENTION AND CONTROL OF WELD DISTORTION

Beginning welders and even those that are more experienced commonly struggle with the problem of weld distortion, (warping of the base plate caused by heat from the welding arc). Distortion is troublesome for a number of reasons, but one of the most critical is the potential creation of a weld that is not structurally sound. This article will help to define what weld distortion is and then provide a practical understanding of the causes of distortion, effects of shrinkage in various types of welded assemblies and how to control it, and finally look at methods for distortion control.



What is Weld Distortion?

Distortion in a weld results from the expansion and contraction of the weld metal and adjacent base metal during the heating and cooling cycle of the welding process. Doing all welding on one side of a part will cause much more distortion than if the welds are alternated from one side to the other. During this heating and cooling cycle, many factors affect shrinkage of the metal and lead to distortion, such as physical and mechanical properties that change as heat is applied. For example, as the temperature of the weld area increases, yield strength, elasticity, and thermal conductivity of the steel plate decrease, while thermal expansion and specific heat increase (Fig. 3-1). These changes, in turn, affect heat flow and uniformity of heat distribution.

Reasons for Distortion

To understand how and why distortion occurs during heating and cooling of a metal, consider the bar of steel shown in Fig. 3-2. As the bar is uniformly heated, it expands in all directions, as shown in Fig. 3-2(a). As the metal cools to room temperature it contracts uniformly to its original dimensions.

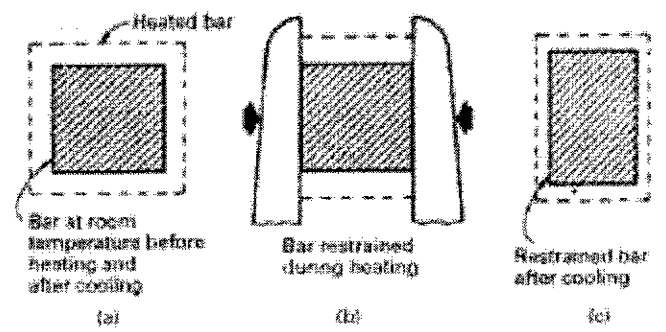


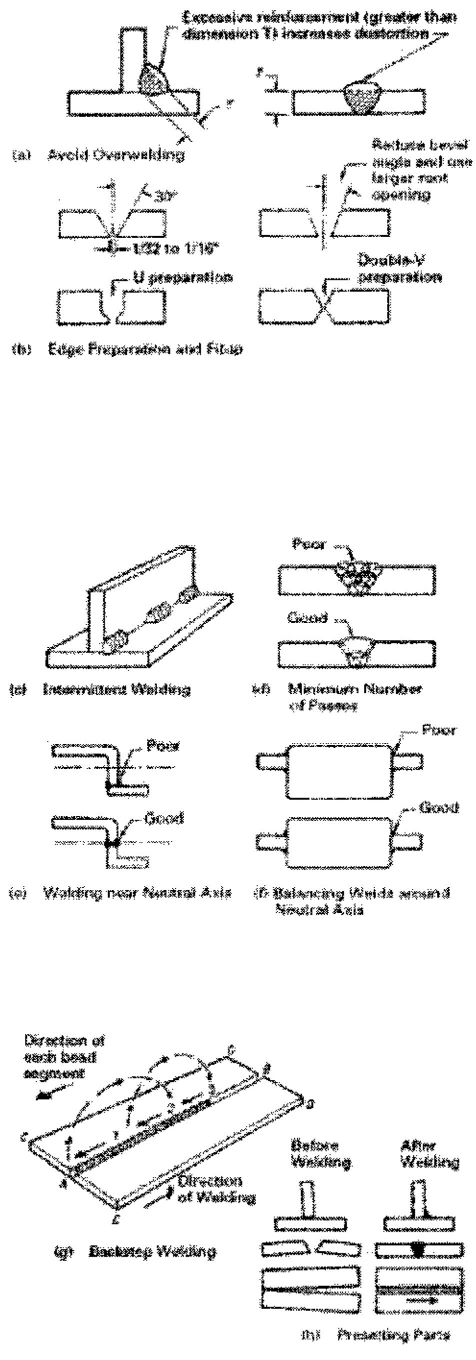
Fig. 3-2 If a steel bar is uniformly heated while unrestrained, as in (a), it will expand in all directions and return to its original dimentions on cooling. If restrained, as in (b), during heating, it can expand only in the vertical direction - become thicker. On cooling, the deformed bar contracts uniformly, as shown in (c), and, thus, is permanently deformed. This is a simplified explanation of basic cause of distortion in welding assemblies.

But if the steel bar is restrained -as in a vise - while it is heated, as shown in Fig. 3-2(b), lateral expansion cannot take place. But, since volume expansion must occur during the heating, the bar expands in a vertical direction (in thickness) and becomes thicker. As the deformed bar returns to room temperature, it will still tend to contract uniformly in all directions, as in Fig. 3-2 (c). The bar is now shorter, but thicker. It has been permanently deformed, or distorted. (For simplification, the sketches show this distortion occurring in thickness only. But in actuality, length is similarly affected.)

In a welded joint, these same expansion and contraction forces act on the weld metal and on the base metal. As the weld metal solidifies and fuses with the base metal, it is in its maximum expanded from. On cooling, it attempts to contract to the volume it would normally occupy at the lower temperature, but it is restrained from doing so by the adjacent base metal. Because of this, stresses develop within the weld and the adjacent base metal. At this point, the weld stretches (or yields) and thins out, thus adjusting to the volume requirements of the lower temperature. But only those stresses that exceed the yield strength of the weld metal are relieved by this straining. By the time the weld reaches room temperature assuming complete restraint of the base metal so that it cannot move the weld will contain locked in tensile stresses approximately equal to the yield strength of the metal. If the restraints (clamps that hold the workpiece, or an opposing shrinkage force) are removed, the residual stresses are partially relieved as they cause the base metal to move, thus distorting the weldment.

Shrinkage Control - What You Can Do to Minimize Distortion
To prevent or minimize weld distortion, methods must be used both in design and during welding to overcome the effects of the heating and cooling cycle. Shrinkage cannot be prevented, but it can be controlled. Several ways can be used to minimize distortion caused by shrinkage:

1. Do not overweld
The more metal placed in a joint, the greater the shrinkage forces. Correctly sizing a weld for the requirements of the joint not only minimizes distortion, but also saves weld metal and time. The amount of weld metal in a fillet weld can be minimized by the use of a flat or slightly convex bead, and in a butt joint by proper edge preparation and fitup. The excess weld metal in a highly convex bead does not increase the allowable strength in code work, but it does increase shrinkage orces.
When welding heavy plate (over 1 inch thick) bevelling or even double bevelling can save a substantial amount of weld metal which translates into much less distortion automatically.
In general, if distortion is not a problem, select the most economical joint. If distortion is a problem, select either a joint in which the weld stresses balance each other or a joint requiring the least amount of weld metal.



2. Use intermittent welding
Another way to minimize weld metal is to use intermittent rather than continuous welds where possible, as in Fig. 3-7(c). For attaching stiffeners to plate, for example, intermittent welds can reduce the weld metal by as much as 75 percent yet provide the needed strength.

3. Use as few weld passes as possible
Fewer passes with large electrodes, Fig. 3-7(d), are preferable to a greater number of passes with small electrodes when transverse distortion could be a problem. Shrinkage caused by each pass tends to be cumulative, thereby increasing total shrinkage when many passes are used.

4. Place welds near the neutral axis
Distortion is minimized by providing a smaller leverage for the shrinkage forces to pull the plates out of alignment. Figure 3-7(e) illustrates this. Both design of the weldment and welding sequence can be used effectively to control distortion.
5. Balance welds around the neutral axis
This practice, shown in Fig. 3-7(f), offsets one shrinkage force with another to effectively minimize distortion of the weldment. Here, too, design of the assembly and proper sequence of welding are important factors.

6. Use backstep welding
In the backstep technique, the general progression of welding may be, say, from left to right, but each bead segment is deposited from right to left as in Fig. 3-7(g). As each bead segment is placed, the heated edges expand, which temporarily separates the plates at B. But as the heat moves out across the plate to C, expansion along outer edges CD brings the plates back together. This separation is most pronounced as the first bead is laid. With successive beads, the plates expand less and less because of the restraint of prior welds. Backstepping may not be effective in all applications, and it cannot be used economically in automatic welding.
7. Anticipate the shrinkage forces

Presetting parts (at first glance, I thought that this was referring to

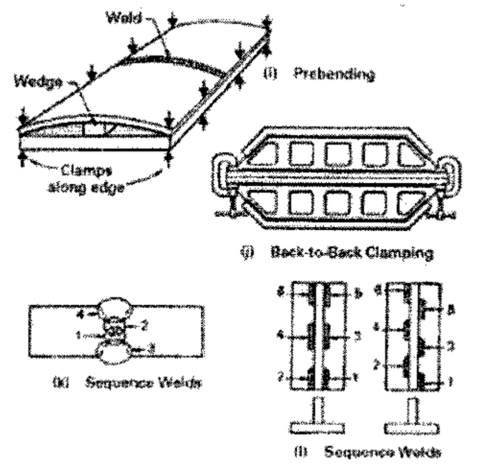


Fig. 3-7 Distortion can be prevented or minimized by techniques that defeat - or use constructively - the effects of the heating and cooling cycle.

overhead or vertical welding positions, which is not the case) before welding can make shrinkage perform constructive work. Several assemblies, preset in this manner, are shown in Fig. 3-7(h). The required amount of preset for shrinkage to pull the plates into alignment can be determined from a few trial welds.

Prebending, presetting or prespringing the parts to be welded, Fig. 3-7(l), is a simple example of the use of opposing mechanical forces to counteract distortion due to welding. The top of the weld groove - which will contain the bulk of the weld metal - is lengthened when the plates are preset. Thus the completed weld is slightly longer than it would be if it had been made on the flat plate. When the clamps are released after welding, the plates return to the flat shape, allowing the weld to relieve its longitudinal shrinkage stresses by shortening to a straight line. The two actions coincide, and the welded plates assume the desired flatness.

Another common practice for balancing shrinkage forces is to position identical weldments back to back, Fig. 3-7(j), clamping them tightly together. The welds are completed on both assemblies and allowed to cool before the clamps are released. Prebending can be combined with this method by inserting wedges at suitable positions between the parts before clamping.

In heavy weldments, particularly, the rigidity of the members and their arrangement relative to each other may provide the balancing forces needed. If these natural balancing forces are not present, it is necessary to use other means to counteract the shrinkage forces in the weld metal. This can be accomplished by balancing one shrinkage force against another or by creating an opposing force through the fixturing. The opposing forces may be: other shrinkage forces; restraining forces mposed by clamps, jigs, or fixtures; restraining forces arising from the arrangement of members in the assembly; or the orce from the sag in a member due to gravity.

8. Plan the welding sequence

A well-planned welding sequence involves placing weld metal at different points of the assembly so that, as the structure shrinks in one place, it counteracts the shrinkage forces of welds already made. An example of this is welding alternately on both sides of the neutral axis in making a complete joint penetration groove weld in a butt joint, as in Fig. 3-7(k). other example, in a fillet weld, consists of making intermittent welds according to the sequences shown in Fig. 3-7(l). In these examples, the shrinkage in weld No. 1 is balanced by the shrinkage in weld No. 2.

Clamps, jigs, and fixtures that lock parts into a desired position and hold them until welding is finished are probably the most widely used means for controlling distortion in small assemblies or components. It was mentioned earlier in this section that the restraining force provided by clamps increases internal stresses in the weldment until the yield point of the weld metal is reached. For typical welds on low-carbon plate, this stress level would approximate 45,000 psi. One might expect this stress to cause considerable movement or distortion after the welded part is removed from the jig or clamps. This does not occur, however, since the strain (unit contraction) from this stress is very low compared to the amount of movement that would occur if no restraint were used during welding.

9. Remove shrinkage forces after welding

Peening is one way to counteract the shrinkage forces of a weld bead as it cools. Essentially, peening the bead stretches it and makes it thinner, thus relieving (by plastic deformation) the stresses induced by contraction as the metal cools. But this method must be used with care. For example, a root bead should never be peened, because of the danger of either oncealing a crack or causing one. Generally, peening is not permitted on the final pass, because of the possibility of covering a crack and interfering with inspection, and because of the undesirable work-hardening effect. Thus, the utility of the technique is limited, even though there have been instances where between-pass peening proved to be the only olution for a distortion or cracking problem. Before peening is used on a job, engineering approval should be obtained.

Another method for removing shrinkage forces is by thermal stress relieving - controlled heating of the weldment to an elevated temperature, followed by controlled cooling. Sometimes two identical weldments are clamped back to back, welded, and then stressrelieved while being held in this straight condition. The residual stresses that would tend to distort the weldments are thus minimized.

10. Minimize welding time
Since complex cycles of heating and cooling take place during welding, and since time is required for heat transmission, the time factor affects distortion. In general, it is desirable to finish the weld quickly, before a large volume of surrounding metal heats up and expands. The welding process used, type and size of electrode, welding current, and speed of travel, thus, affect the degree of shrinkage and distortion of a weldment. The use of mechanized welding equipment reduces welding time and the amount of metal affected by heat and, consequently, distortion. For example, depositing a given-size weld on thick plate with a process operating at 175 amp, 25 volts, and 3 ipm requires 87,500 joules of energy per linear inch of weld (also known as heat input). A weld with approximately the same size produced with a process operating at 310 amp, 35 volts, and 8 ipm requires 81,400 joules per linear inch. The weld made with the higher heat input generally results in a greater amount of distortion. (note: I don't want to use the words "excessive" and "more than necessary" because the weld size is, in fact, tied to the heat input. In general, the fillet weld size (in inches) is equal to the square root of the quantity of the heat input (kJ/in) divided by 500. Thus these two welds are most likely not the same size.

Other Techniques for Distortion Control
Water-Cooled Jig

Various techniques have been developed to control distortion on specific weldments. In sheet-metal welding, for example, a water-cooled jig (Fig. 3-33) is useful to carry heat away from the welded components. Copper tubes are brazed or soldered to copper holding clamps, and the water is circulated through the tubes during welding. The restraint of the clamps also helps minimize distortion.

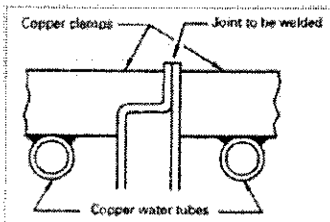


Fig. 3-33 A water-cooled jig for rapid removal of heat when welding sheet meta.

Strongback
The "strongback" is another useful technique for distortion control during butt welding of plates, as in Fig. 3-34(a). Clips are welded to the edge of one plate and wedges are driven under the clips to force the edges into alignment and to hold them during welding.Thermal Stress Relieving Except in special situations, stress relief by heating is not used for correcting distortion. There are occasions, however, when stress relief is necessary to prevent further distortion from occurring before the weldment is finished.

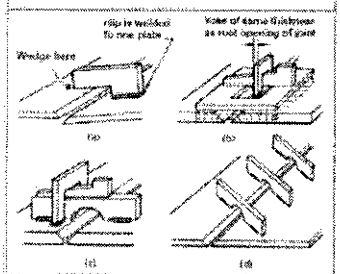


Fig. 3-34 Various strongback arrangements to control distortion during butt-welding.

Summary: A Checklist to Minimize Distortion
In summary, follow the checklist below in order to minimize distortion in the design and fabrication of weldments:

- Do not overweld.
- Control fitup.
- Use intermittent welds where possible and consistent with design requirements.
- Use the smallest leg size permissible when fillet welding.
- For groove welds, use joints that will minimize the volume of weld metal. Consider double-sided joints instead of single-sided joints.
- Weld alternately on either side of the joint when possible with multiple-pass welds.
- Use minimal number of weld passes.
- Use low heat input procedures. This generally means high deposition rates and higher travel speeds.
- Use welding positioners to achieve the maximum amount of flat-position welding. The flat position permits the use of large-diameter electrodes and high-deposition-rate welding procedures.
- Balance welds about the neutral axis of the member.
- Distribute the welding heat as evenly as possible through a planned welding sequence and weldment positioning.
- Weld toward the unrestrained part of the member.
- Use clamps, fixtures, and strongbacks to maintain fitup and alignment.
- Prebend the members or preset the joints to let shrinkage pull them back into alignment.

- Sequence subassemblies and final assemblies so that the welds being made continually balance eac

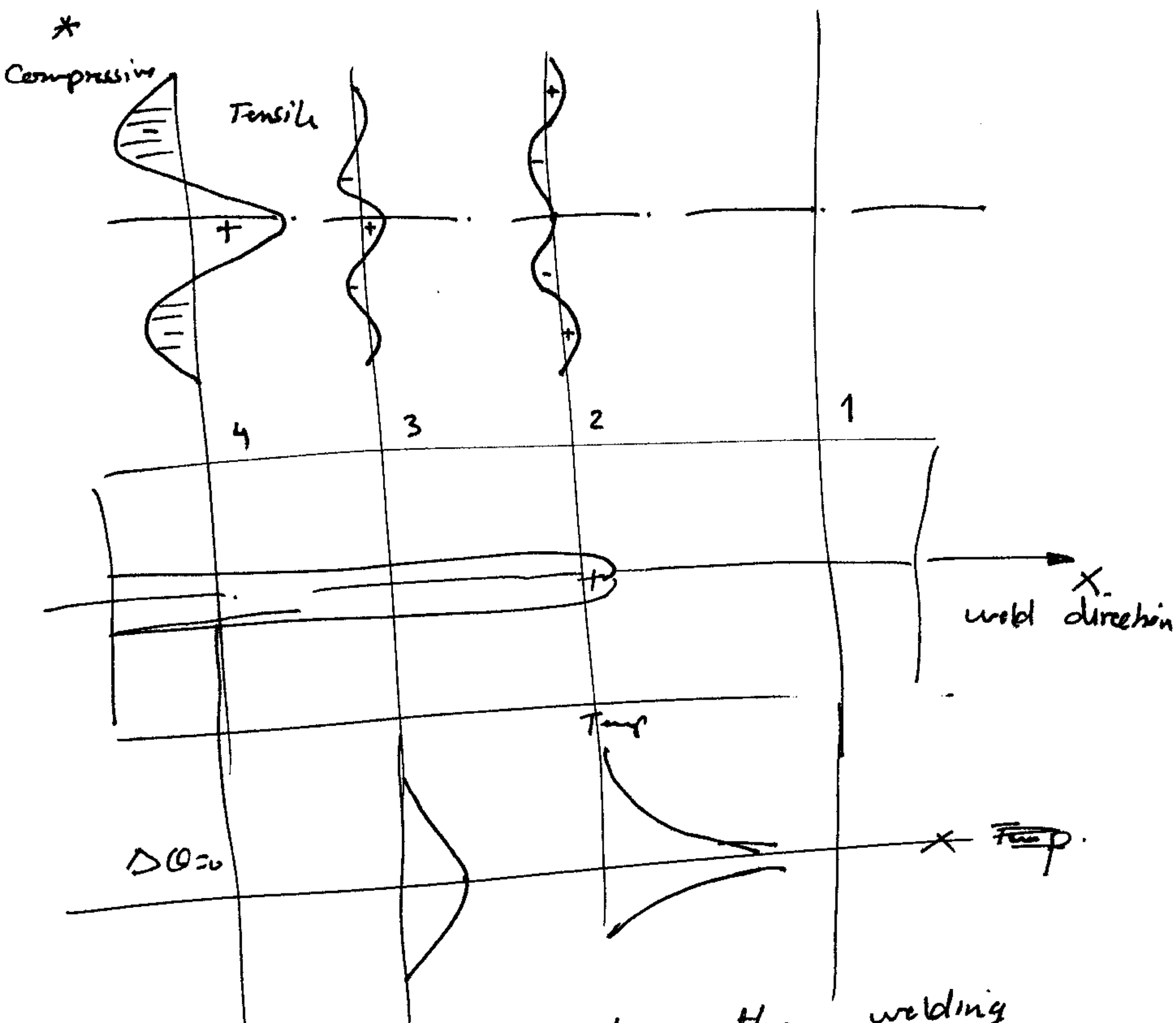
Residual stresses and distortion of weld

1. Residual stresses in welding:

* Changes of stresses during welding both in the weld and ~~base~~ metal are as a result of ~~heating~~ welding heat source acting.

* changes of temperature and resulting stresses are varying along the weld line.

*

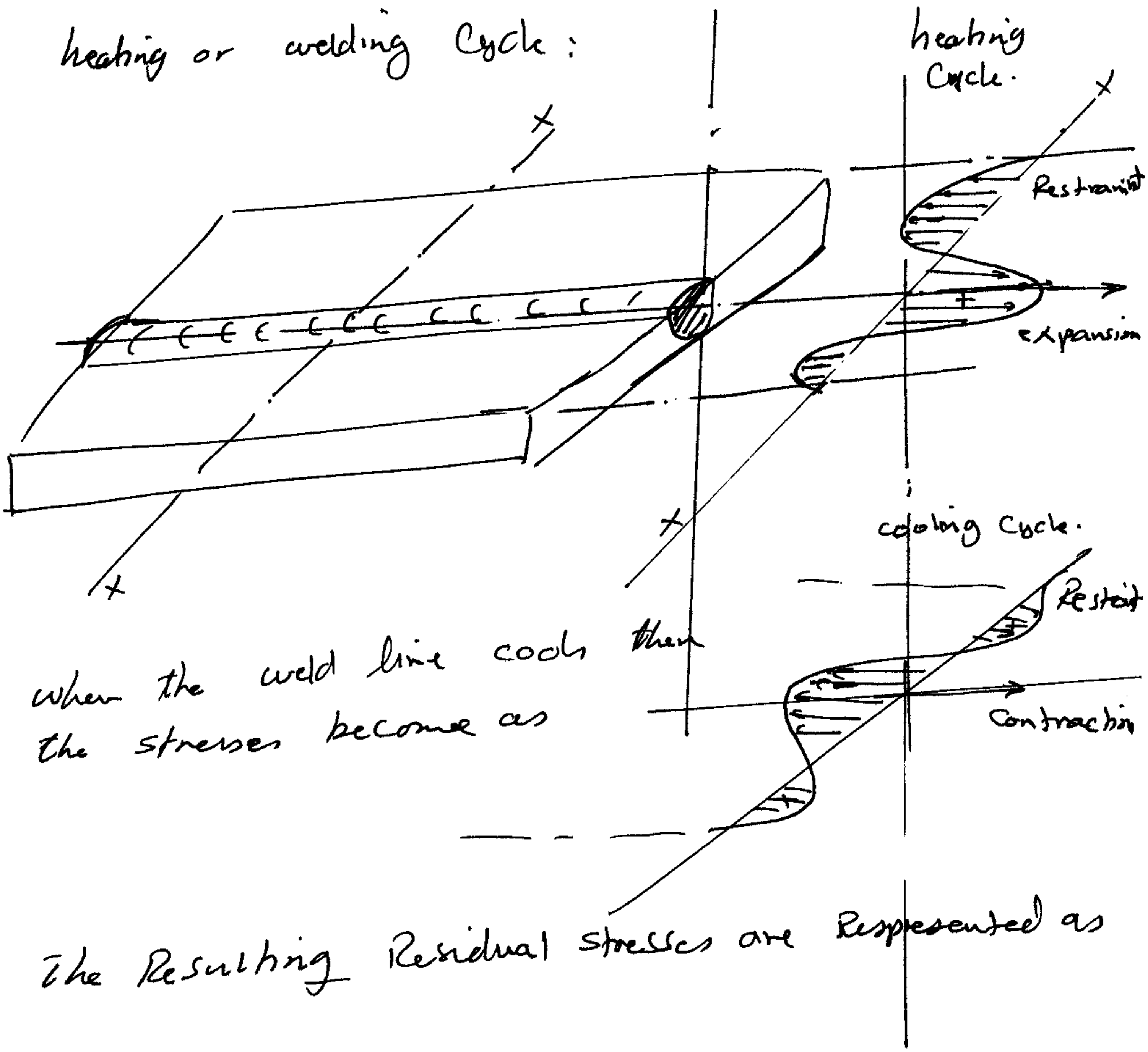


The stresses induced along the welding process.

* Residual stresses are produced during welding when ~~a~~ the heating Cycle is complete.

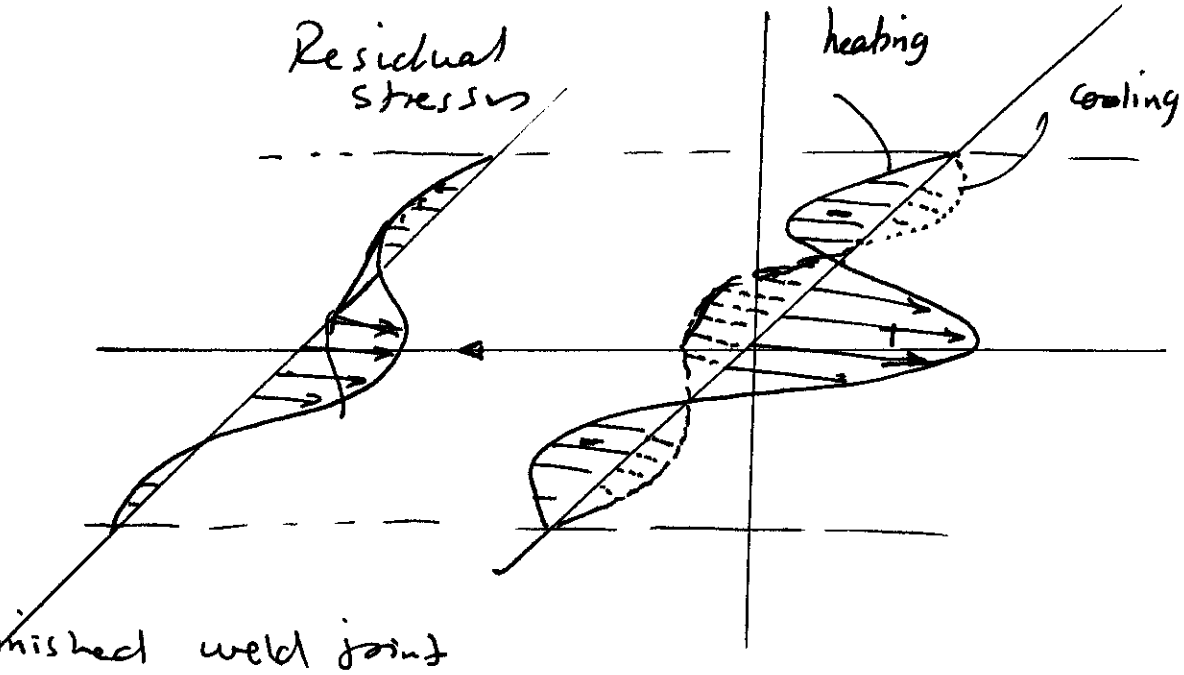
* How the Residual stresses are induced is shown by the following sketches.

heating or welding Cycle :



when the weld line cools then the stresses become as

The Resulting Residual stresses are Respresented as

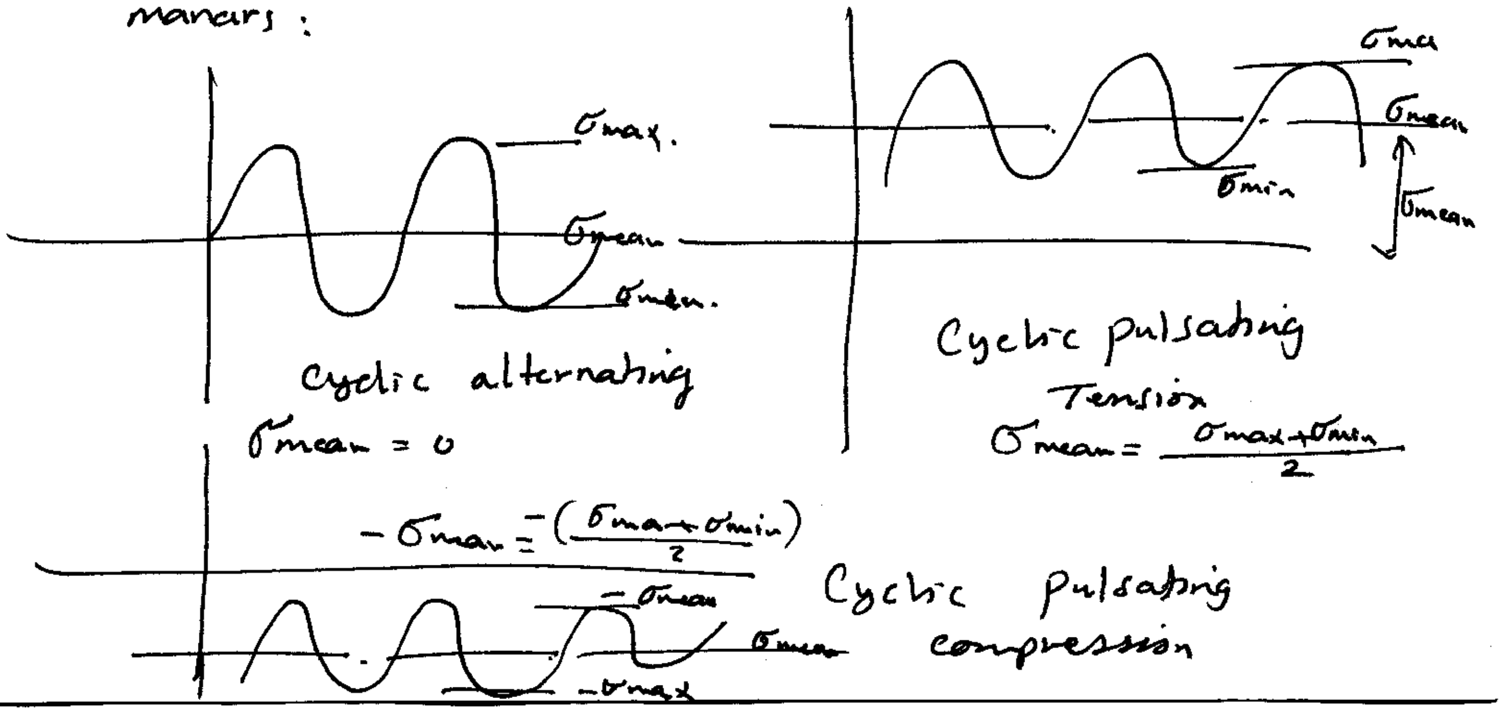


The finished weld joint

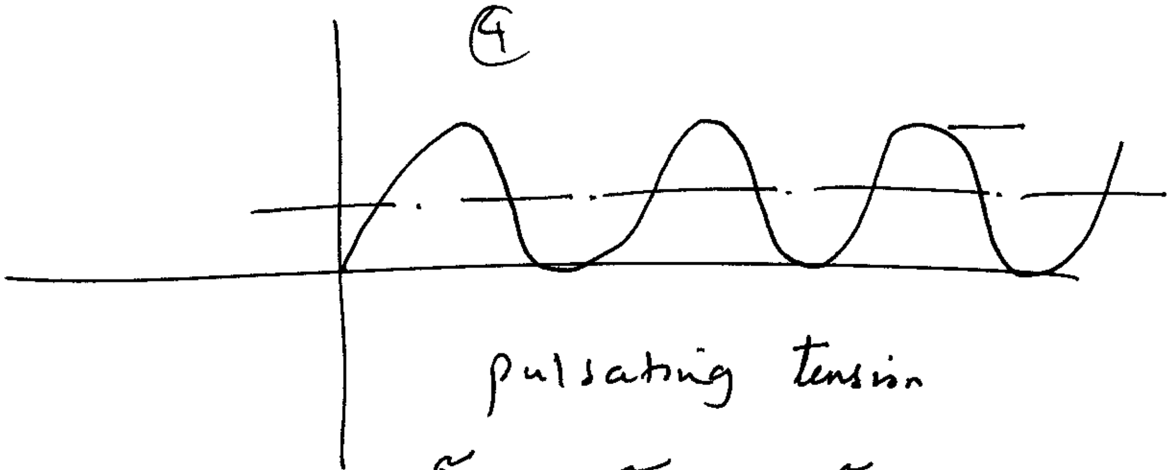
Effects of Residual stresses on the weld joint performance:

1. Effect of residual stresses on fatigue life:

fatigue stresses may be one of the following manars:



④



$\sigma_{max} - \sigma_{min} = \sigma_{max}$

$\sigma_{min} = 0$

$\sigma_{mean} = \frac{\sigma_{max}}{2}$

* if the resulting residual stresses are mainly tensile at the weld line and near by the weld line (heat affected zone).

* So fatigue life under tensile pulsating tension is reduced because the mean stresses is increased

* if the fatigue stresses is compressive so tensile residual stresses increases fatigue life.

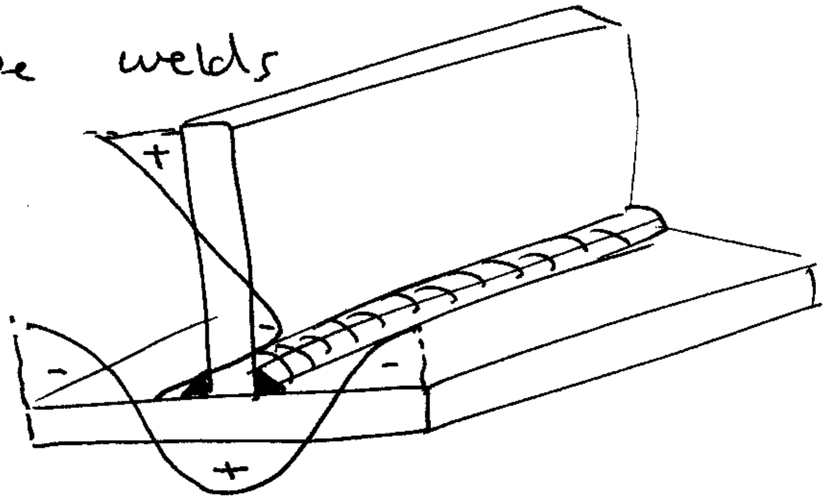
② - Frature toughness of welds.

High tensile residual stresses along the weld line and at adjacent zones lowers the fracture toughness and increases crack propagation. velocity

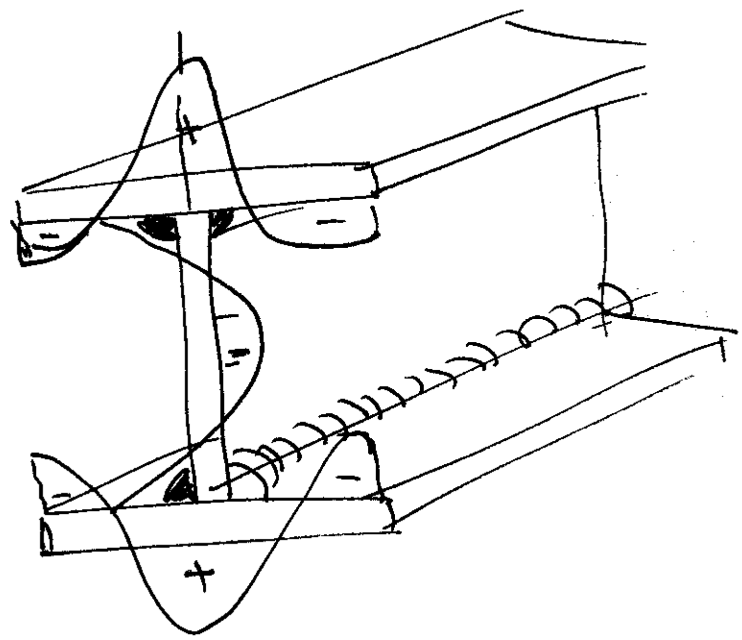
③ - Higher residual stresses than the yield strength of the weld metal & adjacent base metals Result in distortion of the welded joint due to differential expansion rates.

Residual stresses in welded shapes are shown below:

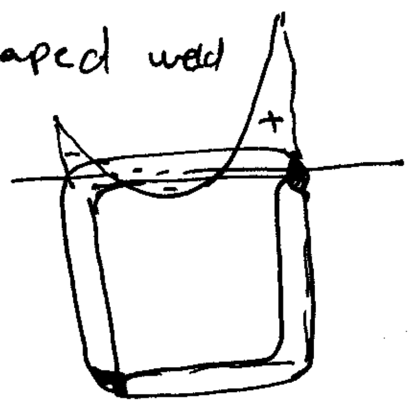
1. T-shape welds



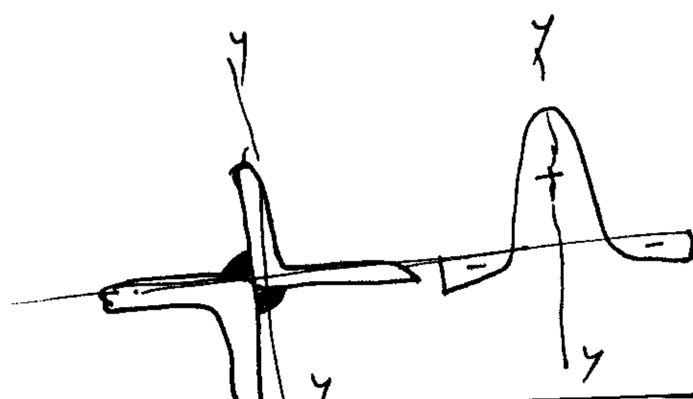
2. H-shaped welds



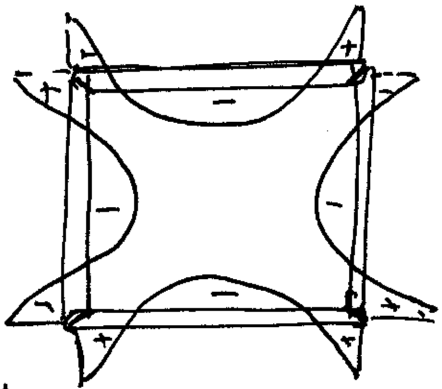
3. □ - shaped weld



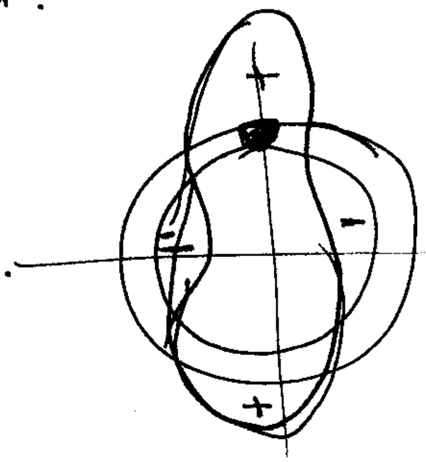
4. X - shaped weld.



5 box - shaped



6 - O - shaped weld.



Residual stress distribution is affected by

1. plate thickness.
2. Boundary restraint applied during the welding.
3. The Heat input supplied (KJ/mm)
4. The effect of post weld heat treatment.
5.

* The nature of the residual stress is that it is self-balancing. There are three fundamental ways through some interaction between residual stress types and structure loading will also occur.

a: Residual stress can be balanced throughout the structure so that members experience tension load and other provide a balancing memberance compressive load

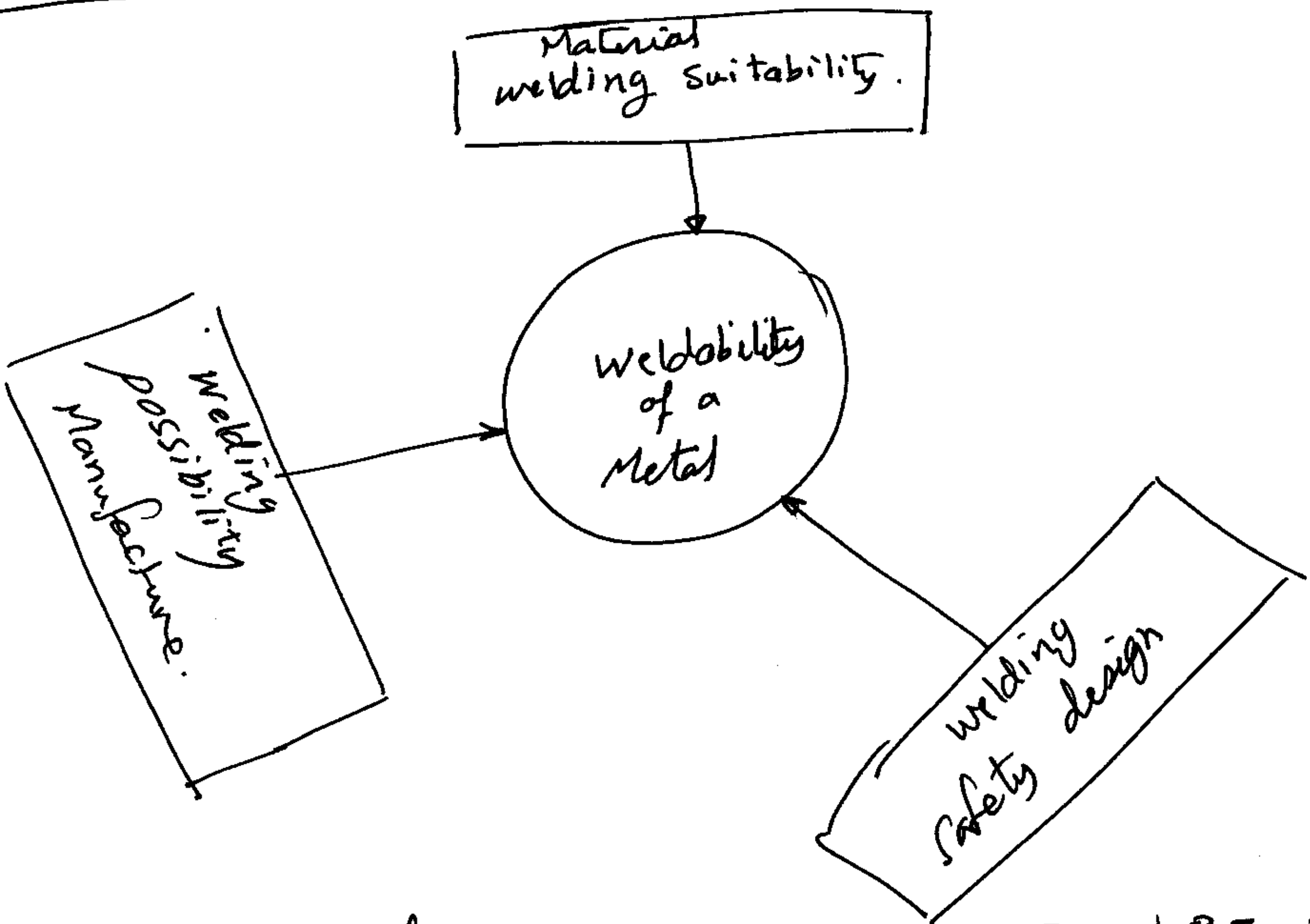
b- Residual stresses can be balanced in the plane of the plate material. an example of this is at the girth weld between tubes where meridian and hoop stresses are in balance

c- Residual stress can be balanced through the thickness of a plate. where the plate surface experience tensile and the plate mid thickness will experience compressive stress.

Weldability of Metals

DIN 8528

(1)



Three outer features according to DIN 8528 part 1

welding Suitability

Chemical composition

* Tendency to hardening
* Tendency to aging.
* Tendency to hot cracking.
* weld pool behavior

Metallurgical properties

* Seggregation
* Inclusions
* Grain size
* Structure
* Anisotropy.

physical properties

* Expansion behavior
* Thermal conductivity
* Melting point
* strength
* Toughness

Welding safety

↓

Welding safety due to design

design

* Power flow in workpiece
* Arrangement of joints
* Material thickness
* Notch effect.
* Stiffness difference.

Stress condition

* Type & level of strain in work piece.
* Dimensional degree of strain.
* Stress speed
* Temp.
* corrosion.

For welding possibility -

welding possibility

↓

welding possibility due to manufact

welding preparation

- welding Method.
- Consumable Typ.
- Joint type.
- Groove shape
- pre heating.
- weather

executing of welding

* Heat control
* Heat input
- welding sequence

Post-treatment

- post heat treatment
- Grinding
- Pickling.

* Weldability: is considered as ease of accomplishing a satisfactory weld joint and can be in determined from quality of the weld joint, effort and cost required for developing the weld joint.

Weldability can be determined by many factors:

- Charactristics of Metal determining the quality of weld joint include:
  1- Tendency to cracking.
  2- Tendency to hardening of HAZ
  3- Tendency to Softening of HAZ
  4- oxidation.
  5- evaporation.
  6- structural modification.
  7- affinity to gases.

Efforts required to produce sound weld joint are determined by properties of metal System.

1. Melting point
2- Thermal expansion Coeff-
3- Thermal & Electrical conductivity.
4- Defects inherent in base Metal
5- Surface conditions.

* All the factors adversely affecting the weld quality and increasing the efforts for producing Satisfactory weld quality, weldability is decreased.

AWS ~~diff~~ difinition of weldability:

The capacity of a metal to be welded under the fabrication conditions imposed into a specific suitabity designed structure and to perform satisfactorily in service.

Weldability of steels:

Factors affecting weldability:

1 - steel composition & pocessing.
2 - weld Metal & HAZ properties
3 - choice of welding ~~properties~~ variables.
4 - pre & post-weld processing.

1. Steel composition & processing.

Weldability of steel and composition

Weldability of steels can be judged by two parameters (a) cleanliness of weld metal and (b) properties of HAZ. Cleanliness of weld metal is related with presence of inclusion in the form of slag or gases whereas HAZ properties are primarily controlled by hardenability of the steel. Proper shielding of arc zone and degassing of molten weld metal can be used to control first factor. Proper shielding can be done by inactive gases released by combustion of electrode coatings in SMA or inert gases (Ar, He, Co_2) in case of TIG, MIG welding. Hardenability of steel is primarily governed by the composition. All the factors increasing the hardenability adversely affect the weldability because steel becomes more hard, brittle and sensitive to fracture/cracking, therefore it needs extra care. So, more the precautions should be taken to produce a sound weld joint.

Addition of all alloying elements (C, Mn, Ni, W, Cr etc.) except cobalt increases the hardenability which in turn decreases the weldability. To find the combined effect of alloying elements on hardenability/weldability, carbon equivalent (CE) is determined. The most of the carbon equivalent (CE) equations used to evaluate weldability depends type of steel i.e. alloy steel or carbon steel.

- Common CE equation for low alloy steel is as under:

$$CE = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$$

(elements are expressed in weight percent amounts)

- For low carbon steels and micro-alloy steels, CE is obtained using following equation: $CE = C + Si/25 + (Mn+Cr)/16 + (Cr+Ni+Mo)/20 + V/15$

- From the Welding Journal, for low carbon, micro-alloyed steels, Ito-Besseyo carbon equivalent:

$$Ceq = C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + Mo/15 + V/10 + 5*B$$

Since the effect of different alloying elements on hardenability of steel is different therefore, their influence on weldability will also be different. In general, high the CE steel needshigh preheat temperature to produce crack free weld joint. Following point can be kept in mind as broad guidelines for welding steel.

- ❖ CE < 0.45 No preheat required,
- ❖ 0.45<CE< 0.7 200-500^{0}C of preheat may be used
- ❖ CE > 0.7 Can not be welded

Thickness of plate to be welded affects the cooling rate which in turn influences the hardening and cracking tendency. To take into account the thickness of plate above criteria is modified to get compensated carbon equivalent (CCE) relation.

$$CCE= CE + 0.00425t$$

Where t is the thickness of plate in mm

- ❖ CCE< 0.4 No preheat required,
- ❖ 0.4<CCE< 0.7 200-500^{0}C of preheat may be used
- ❖ CCE> 0.7 Cannot be welded

From the weldability point of view, steels can be placed in five categories based on chemical composition, mechanical properties, heat treatment conditions, and high temperature properties: a) carbon steel, b) high strength low alloy steel, c) quench and tempered steel, d) heat treatable steel and e) Cr-Mo steel. These steels need to be welded in different forms such as sheets, plates, pipes, forgings etc. In case of steel welding, it is important to consider thickness of base metal as it affects the heat input, cooling rate and restraint conditions during welding.

37.3 Different types of steel and welding

Carbon steel generally welded in as rolled condition (besides annealed and normalized one). The weldablecarbon steel is mostly composed of carbon about 0.25 %, Mn up to 1.65%, Si up to 0.6% with residual amount of S and P below 0.05%. High strength low alloy steel (HSLA) is designed to have yield strength in range of 290-550 MPa using alloying concentration lesser than 1% in total. These

Lecture 37

Weldability of Metals I

This chapter presents the concept of weldability of metals and factors affecting the same. Different parameters that are used as a measure of weldability have been elaborated. Attempts have been made to describe the relationship between carbon equivalent, hardenability and cracking tendency of weld joints of steel.

Keywords: Weldability, measures of weldability, carbon equivalent, cracking of HAZ, hardenability, austenitic electrode

37.1 Understanding weldability

Weldability is considered as ease of accomplishing a satisfactory weld joint and can be in determined from quality of the weld joint, effort and cost required for developing the weld joint. Quality of the weld joint however, can be determined by many factors but the weld must fulfill the service requirements. The characteristics of the metal determining the quality of weld joint includes tendency to cracking, (1) (2) hardening and softening of HAZ, (3) oxidation, (4) evaporation, (5) structural (6) modification and (7) affinity to gases. While efforts required for producing sound weld joint are determined by properties of metal system in consideration namely melting point, 1 2 thermal expansion coefficient, 3 thermal and electrical conductivity, 4 defects inherent in base metal and 5 surface condition. All the factors adversely affecting the weld quality and increasing the efforts (& skill required) for producing a satisfactory weld joint will in turn be decreasing the weldability of metal. *

In view of above, it can be said that weldability of metal is not an intrinsic property as it is influenced by a) all steps related with welding procedure, b) purpose of the weld joints and c) fabrication conditions. Welding of a metal using one process may show poor weldability (like Al welding with SMA welding process) and good weldabilitywhen the same metal is welded with some other welding process (Al welding with TIG/MIG). Similarly, a steel weld joint may perform well under normal atmospheric conditions and the same may exhibit very poor toughness and ductility at very low temperature condition. Steps of the welding procedure namely preparation of surface and edge, preheating, welding process, welding parameters, post weld treatment such as relieving the residual stresses, can influence the weldability of metal appreciably. Therefore, weldability of a metal is considered as a relative term.

37.2 Weldability of steels

To understand the weldability of steel, it important to look into the different phases, phase mixtures and intermetallic generally found in steel besides the changes in phase that can occur during welding due to heating and cooling cycles. All these aspects can be understood by going through following section presenting significance of Fe-C diagram, time-temperature-transformation diagram and continuous cooling transformation diagram.

Fe-C Equilibrium Phase Diagram

Fe-C diagram is also called iron-iron carbide diagram because these are the two main constituents observed at the room temperature in steel while the presence of other phases depends on the type and amount of alloying elements. It shows the various phase transformations as a function of temperature on heating / cooling under equilibrium conditions (Fig. 37.1).

Allotropy and critical temperatures

Change in crystal structure of an element with rise in temperature is termed as allotropy. Iron shows the allotropic behaviour at temperature 910^{0}C and 1390^{0}C. Iron changes its crystal structure first from BCC to FCC at 910^{0}C and then from FCC to BCC at 1390^{0}C. Therefore, solubility of carbon in iron varies with temperature especially above 910^{0}C and 1390 ^{0}C.

Isothermal Transformations in Fe-C diagram

Three are main reaction points in Fe-C diagram namely peritectic, eutectoid and eutectic, which are of great academic and practical importance. All three reactions take place at a fixed temperature and composition.

Peritecitc reaction

$$\text{Liquid metal} + \delta\text{-iron (B. C. C.)} \xrightleftharpoons{1495\ ^0\text{C and } 0.18\%\ \text{C}} \gamma\text{-iron (F. C. C.)}$$

Eutectic reaction

$$\text{Liquid metal} \xrightleftharpoons{1130\ ^0\text{C and } 4.3\%\ \text{C}} \gamma\text{-iron (F. C. C.)} + Fe_3C$$

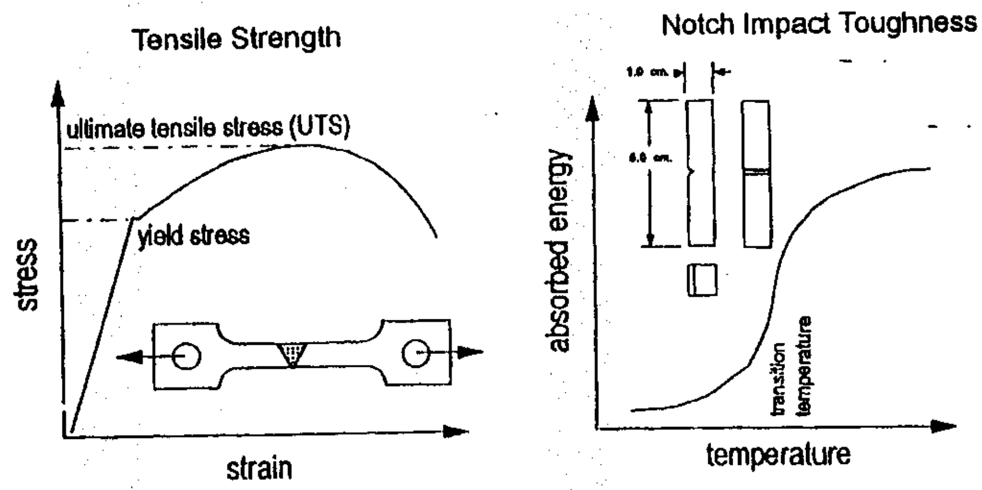
weldability of steels.

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



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

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

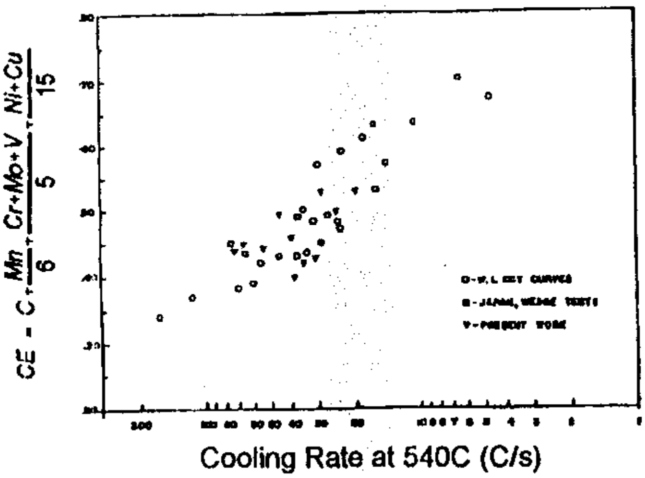
- Steel *hardenability* can be correlated with the *carbon equivalent (CE), e.g.:*

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

- 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



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

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

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welding defects

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.*

Hydrogen Induced Cracking

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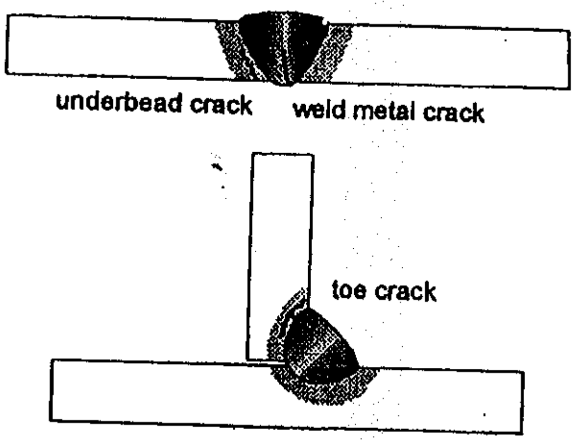
Typical Forms of HIC



Causes of HIC

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

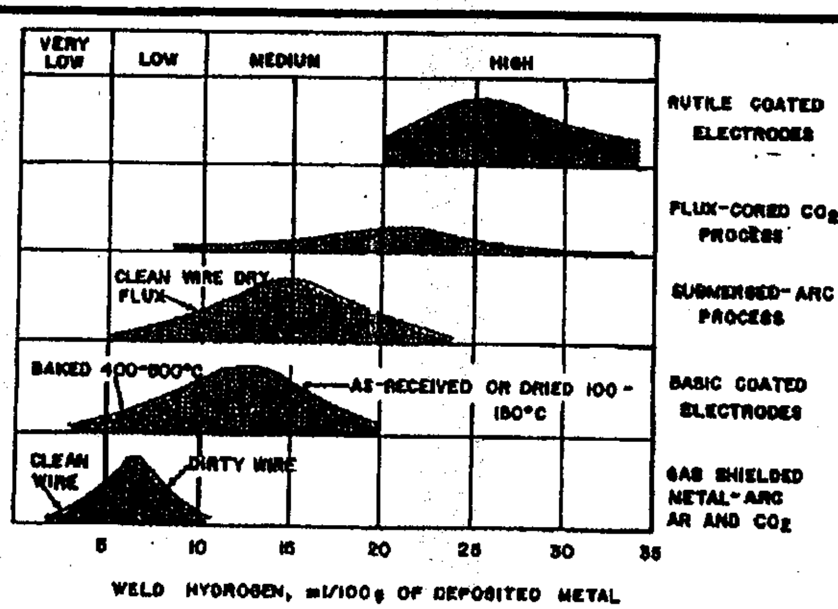
1. hydrogen in the weld metal
2. a crack-sensitive microstructure
3. tensile stress
4. temperatures below 200 C

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

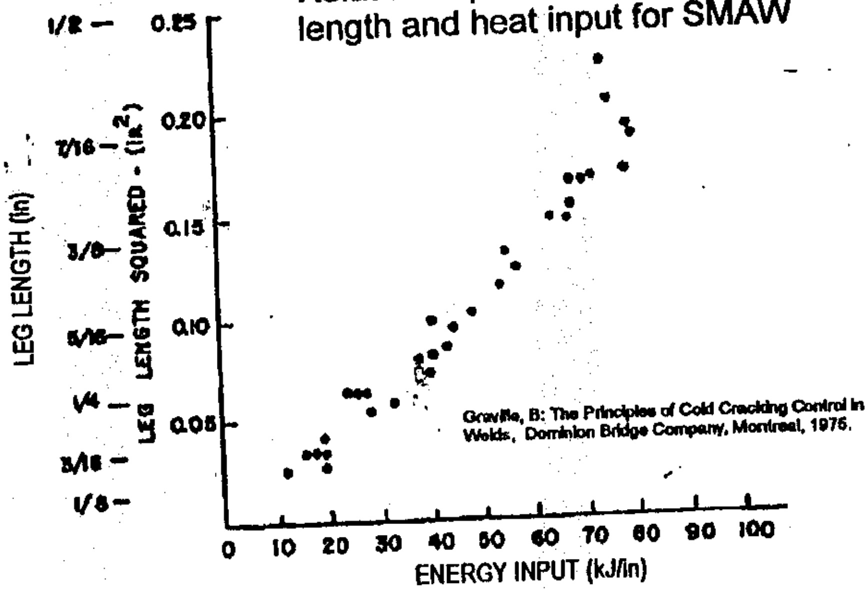
4- Temperature

- 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

1 - Use low-hydrogen welding processes
  - baked basic electrodes or fluxes
  - gas shielded processes (GMAW, GTAW or PAW)
  - ensure cleanliness and freedom from contaminants
2 - control steel composition
  - carbon equivalent < 0.45
3 - reduce cooling rates and peak HAZ hardness (dependent on thickness and CE)
  - preheat joint
  - minimum heat input, bead area or fillet weld size
4 - 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

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.

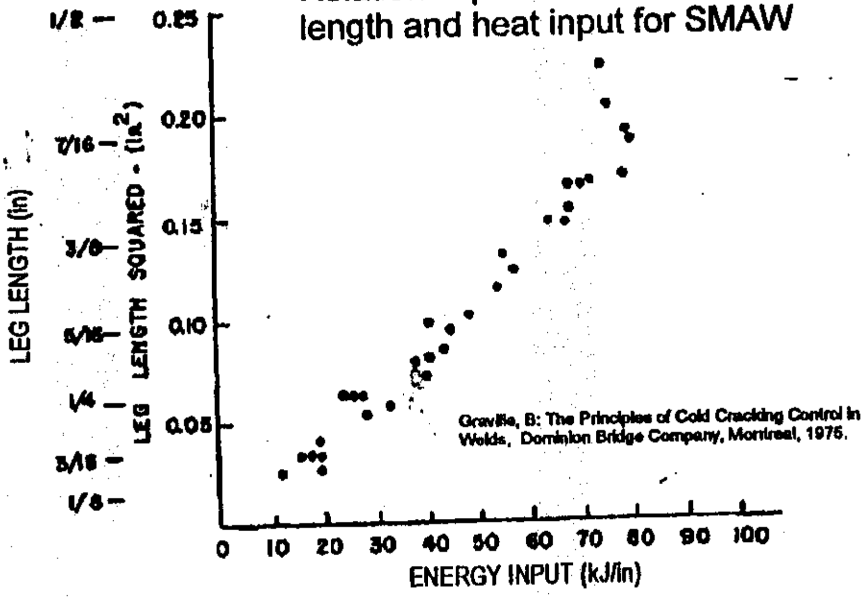
Causes of HIC

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

HIC-Avoidance

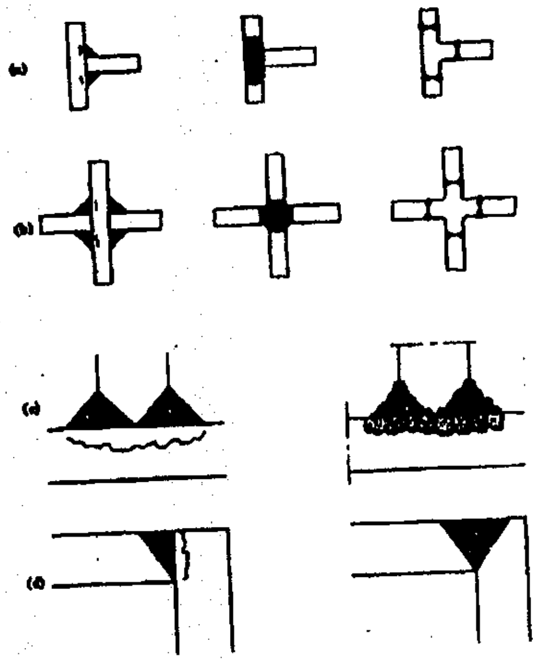
Relationship between fillet weld leg length and heat input for SMAW



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, H2, N2, and H2S.
- 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.