TOWARDS GOOD WELDING PRACTICE

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ABSTRACT

The paper is a review of various aspects of good welding practice in a broad sense of the term. Welding is a common and efficient mode of joining two metal workpieces. At the same time, it is one of the most difficult and demanding of connection technologies. The paper covers various factors and different considerations in the practice of welding: planning, weldability of different steels, selection of electrodes, design, code provisions, fabrication, personnel, environment, defects and remedies, shrinkage and distortion, inspection, testing, and safety. Special attention is paid to causes and consequences, and to the avoidance and repair, of various defects, such as cracking, porosity, slag inclusion, etc. Guidelines for economical and efficient welding are listed under various heads.

1. INTRODUCTION

Welding is a very economical and effective method of joining metals. However, it is a complex process involving the interaction of many physical, chemical, environmental, and human factors, and demands serious and continuous attention to numerous details.

Good welding is as much art and skill as it is science and technology. It must be done right the first time, because otherwise, it will be costlier and more time consuming to correct any flaws or deficiencies later, than to have exercised more care – and invested somewhat more funds – the first time.

Efforts towards good welding must start at the planning stage, should continue through selection of materials, choice of processes, careful design, proper environment, skilled personnel, and diligent supervision, and would end with adequate testing and appropriate corrective measures.

Omer W. Blodgett, the pioneer and doyen of welding, lists the following five P's for good structural welding, in his book *Design of Welded Structures* (1996):

1. **P**rocess: The right welding process for the job

2. **P**reparation: Joint preparation compatible with the process
3. **P**rocedures: Detailed procedures essential for uniform results
4. **P**ersonnel: Appropriate qualified personnel assigned to the job
5. **P**roof: Suitable pre-test procedures to ensure good quality.

Many of these aspects will be covered in the following sections.

2. PLANNING

One wag is quoted to have said, the best weld is no weld. Although it sounds facetious, the germ of truth in it implies, no welding should be done if the same ends can be achieved less expensively and more effectively by other means. That is because there are so many variables in welding that at any stage, a trivial flaw can jeopardise the entire purpose of welding. If there is uncertainty in even one of the major factors in the welding operation, it is better not to do it than botch it up.

The general rule "Shop welding, field bolting" is common universal practice, particularly where labour costs are high and weather conditions are widely variable. In Singapore, a lot of field welding is done, and this needs special care.

All the factors involved in a job must be carefully evaluated in terms of predictability and control. Low temperature, confined space, heights and related wind forces, whether manual or automatic, and so on, right down to whether the welder had a fight with his wife, will have an impact on the quality of the weld.

One of the main concerns in planning will be access to the weld sites by electrodes, as well as welding equipment and accessories. Failure to check this aspect may result in frustration, delay, and expense of modifications later.

Checking out the positions of various welds on the job would be especially important because of the wide differences in time, quality, and expense between flat (downhand) welding and overhead (uphand) welding. Figure 1 depicts the various positions with reference to fillet welds.

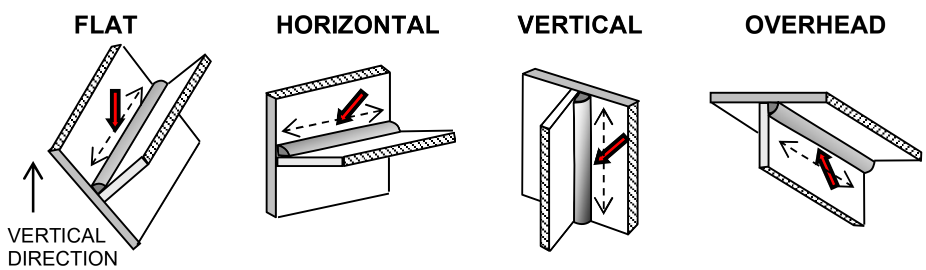

Figure 1 : Welding Positions (Bold full-line arrows denote general nozzle direction; double headed broken line arrows show welding direction.)

Overhead welding involves too many uncertainties and risks. In shop welding, it may be possible to turn the job upside down so that the welder could weld flat, rather than overhead.

3. WELDABILITY

Almost any two metals may be welded together. But welding is more cost-effective and more dependable for certain combination of materials than for others, the distinguishing characteristic being called "Weldability".

Thus, weldability is a measure of how easy it is to: (a) Obtain crack-free welds, (b) Achieve adequate mechanical properties, and, (c) Produce welds resistant to service degradation.

Weldability is not a fixed parameter for a given material, but will depend on joint details, service requirements, and the welding processes and facilities available.

3.1. Weldability of Steel Groups

"*Welding – Guidelines for a metallic material grouping system (ISO/TR 15608:2000)*" identifies a number of steel groups which have similar metallurgical and welding characteristics. The main characteristics and risks in welding these groups are as follows:

Group 1. Low carbon unalloyed steels, no specific processing requirements, $p_y \leq 460MPa$:

For thin sections, unalloyed materials, these are normally readily weldable. However, when welding thicker sections with a flux process, there is a risk of HAZ ("Heat Affected Zone") hydrogen cracking, which will need increased hydrogen control of the consumables or the use of preheat.

Group 2. Thermo-mechanically treated fine grain steels and cast steels, $p_y > 360$ MPa:

For a given strength level, a thermo-mechanically processed (TMCP) steel will have a lower alloy content than a normalised steel, and thus will be more readily weldable with regard to avoidance of HAZ hydrogen cracking and the achievement of maximum hardness limits. However, there is always some degree of softening in the HAZ after welding TMCP steels, and a restriction on the heat input used, so as not to degrade the properties of the joint zone (e.g. ≤ 2.5 kJ/mm limits for 15mm plate).

Group 3. Quenched and tempered steels and precipitation hardened steels (except stainless steels), $p_y > 360$ MPa:

These are weldable, but care must be taken to adhere to established procedures, as these often have high carbon contents, and thus high hardenability, leading to a hard HAZ susceptibility to cracking. As with TMCP steels, there may be a restriction on heat input or pre-heat to avoid degradation of the steel properties.

Groups 4, 5 and 6. Chromium-molybdenum and chromium-molybdenum-vanadium creep resisting steels:

These are susceptible to hydrogen cracking, but with appropriate pre-heat and low hydrogen consumables, with temper bead techniques to minimise cracking, the steels are fairly weldable. Postweld heat treatment is used to improve HAZ toughness in these steels.

Group 7. Ferritic, martensitic or precipitation hardened stainless steels:

When using a filler to produce matching weld metal strength, pre-heat is needed to avoid HAZ cracking. Postweld heat treatment is essential to restore HAZ toughness.

Group 8. Austenitic stainless steels:

These steels do not generally need pre-heat, but in order to avoid problems with solidification or liquation cracking upon welding, the consumables should be selected to give weld metal with a low impurity content, or if appropriate, residual ferrite in the weld metal.

Group 9. Nickel alloy steels, Ni ≤ 10%:

These have a similar weldability to Groups 4, 5 and 6.

Group 10. Austenitic ferritic stainless steels (duplex):

In welding these steels, maintaining phase balance in the weld metal and in the HAZ requires careful selection of consumables, the absence of pre-heat and control of maximum interpass temperature, along with minimum heat input levels, as slow cooling encourages austenite formation in the HAZ.

Group 11. High carbon steels:

These steels will be less weldable owing to their increased carbon content with respect to Group 1. It is likely that care over the choice of consumables and the use of high pre-heat levels would be needed.

It is important to obtain expert advice before welding any steels in which experience is lacking.

3.2. Preferred Composition of Carbon Steel

"Design of Welded Structures" by Blodgett, published in 1966, still being reprinted and considered the bible for welding, lists the following composition for carbon steel as best for weldability:

Carbon	0.06 - 0.25%	(0.35%)
Manganese	0.35 – 0.80%	(1.40%)
Silicon	0.10% max.	(0.30%)
Sulphur	0.035% max	(0.05%)
Phosphorus	0.03% max	(0.04%)

The bracketed numbers in the above list denote the limiting percentage beyond which extra care may be required in welding.

3.3. Carbon Equivalent Value

A measure of whether a steel can be easily welded is to determine the carbon equivalent value (C_{eq} or C^{*}_{eq}) of the steel. There are a number of different equations that can be used for this, depending on the type of steel. Carbon (C), and the alloy additions Copper (Cu), Chromium (Cr), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Silicon (Si), and Vanadium (V) are expressed in %.

For low alloy C-Mn steels with a ferrite + pearlite structure:

$$C_{eq} = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15 \quad \ldots (1)$$

For modern low carbon steels:

$$C^{*}_{eq} = C + Si/25 + (Mn+Cr)/16 + (Cr+Ni+Mo)/20 + V/15 \quad \ldots (2)$$

For steel to be easily weldable, C_{eq} should be less than about 0.4%, and C^{*}_{eq} should be less than about 0.25%.

A slight modification of Eq. (1) is that with the addition of (Si/6), the value should be less than 0.48%.

Another comprehensive carbon equivalent formula is:

$$C_{eq} = C + Mn/6 + Ni/20 + Cr/10 + Cu/40 - Mo/50 - V/10 \quad \ldots (3)$$

If $C_{eq} < 0.40\%$, material is readily weldable

If C_{eq} between 0.40% and 0.55%, use of pre-heat or low-hydrogen electrodes is suggested

If $C_{eq} > 0.55\%$, special precautions will be required to avoid cracks

Carbon equivalent value is also useful to determine pre-heat requirements. For instance, with:

$$C_{eq} = C + Mn/6 + Ni/15 + Cr/5 + Cu/13 + Mo/4 \quad \ldots (4)$$

If $C_{eq} < 0$ to 0.45%, pre-heating optional

If C_{eq} between 0.45% to 0.60%, pre-heating 200°-400°F

If $C_{eq} > 0.60\%$, pre-heating 400°-700°F

3.4. Arc Weldability of Dissimilar Metals

When arc welding two dissimilar materials, there are a number of factors that need to be addressed, in addition to those associated with welding similar materials.

Firstly, from a practical viewpoint, it may not be possible to make a fusion weld if the melting points of the two materials are too different, as it is essential to have controlled melting on both sides of the joint simultaneously. Secondly, even if this criterion is met, it may not be possible to produce an adequate joint if the two materials are metallurgically incompatible.

Metallurgical incompatibility may lead to uncontrollable weld metal/HAZ cracking or a weld metal microstructure that cannot provide adequate mechanical or corrosion performance, e.g. containing unacceptable martensite or intermetallic phases.

Even when cracking can be avoided and suitable weld metal deposited, other potential problems may arise. Adjacent to the fusion boundary there will be a band, typically very narrow, whose microstructure may be unacceptable for service.

Undesirable "Unmixed zones", or "partially mixed zones" consisting of fused parent material, which has not mixed fully with the bulk weld metal, e.g. due to differences in melting point, may also form adjacent to the fusion boundary.

When arc welding dissimilar metals, “arc blow” or uncontrollable deflection of the arc may occur due to the flow of thermoelectric currents between the hot and cold parts of the joint, and hence the development of magnetic fields, in a similar way to the operation of a thermocouple.

When two materials are metallurgically incompatible, it may be possible to make a satisfactory weld by addition of a suitable filler metal. This is exemplified by the joining of steels and stainless steels, with a filler metal that is resistant to both solidification cracking and hydrogen cracking.

Frequently, where a welding consumable with composition similar to one of the steels is not appropriate, a nickel based filler may be adopted. In addition, these may be used for welding of steels to some copper alloys due to their tolerance to dilution by a range of alloying elements without a phase change.

4. ELECTRODES

Electrodes and the corresponding current must be carefully chosen to suit the particular job, as listed for common applications in Table 1.

Table 1 : Choice of Electrode and Current for Common Applications

Electrode	*Current*	*Applications*
E6010	DC+	For dirty, rusty, greasy, or painted steel, especially in vertical or overhead applications.
E6011	AC DC±	For: (a) Sheet metal welding applications and AC pipe welding, particularly where the steel is not clean; and, (b) Small AC welders, offering high arc stability for excellent performance with power sources as low as 50Vopen-circuit voltage (OCV), and ability to start easily on low open circuit voltage welders.
E6012	DC- AC	Versatile, high speed electrode for: (a) Sheet metal lap joints and fillet welds; and, (b) Poor fit-up jobs.
E6013	AC DC±	For: (a) Low amperage welding on sheet metal - especially in applications where appearance is important; (b) Smaller AC welders with low open-circuit voltages; and, (c) Jobs involving irregular or short welds that require a change in position.
E7014	AC DC±	High deposition rates for fast performance. Easy-to-use, all-position electrode for: (a) Sheet metal lap joints and fillet welds; and, (b) General purpose plate welding, and, (c) Maintenance jobs.
E7018 H8	AC DC±	For low, open-circuit voltage AC power sources. Cold re-strikes are no problem.
E7018 H4R	DC+ AC	For mild steel and some high-strength low-alloy steels. Also tolerates high sulphur and high silicon steels. Features higher tensile strength for stress-relieved properties.

5. DESIGN CONSIDERATIONS

Good design involves not only good strength but also good configuration of the weld group.

The theoretical analysis underlying the design principles and codes is often quite basic, actually purposely simplified because of the complexity of the actual stress distribution.

Welds are treated as line elements, and all the variations and combinations of stresses are reduced to the simplest possible form, namely, a constant shear stress across the minimum weld area, that is, the “throat”.

Design, usually by iterative analysis in a general case (not available from tables), is fairly straightforward as long as the stress components due to forces and moments lie in a plane. However, if the actions are three-dimensional, then the resulting stresses will depend on the signs of the moment effects, and one would need a definitive procedure, and an unambiguous sign convention, to obtain the correct algebraic summations.

Under these circumstances, computer programs come in handy. The author developed a program “WeldPAD” (standing for Weld Properties, Analysis, and Design) to compute the x, y, z stress components of any planar weld group subjected three-dimensional forces and moments, and further compute the weld size and the iterative interaction equation values, according to according to BS5950.

5.1. Code Provisions for Design

Many of the theoretical considerations for stress analysis are modified by experimental findings and reduced to simple design procedures. Different codes handle this kind of adjustment in different ways.

A case in point is the recognition of the higher strength of transverse welds compared to longitudinal welds.

American Welding Society (AWS) and American Institute of Steel Construction (AISC) include this increased strength in tables and a formula involving the angle of a single force with the transverse segment. AISC Specification Appendix J2.4 provides a means to take advantage of this strength increase. This is particularly useful for transverse stiffener end welds, which are purely transversely loaded and qualify for a full 50 percent increase in shear strength.

As an alternative to the "Simple Method" of taking the vectorial sum of all three components as critical, BS5950 proposes the "Directional Method", with an interaction formula considering the extra strength of transverse welds.

Unfortunately, as shown in Ref. 21, much of this benefit for transverse welds may be lost when the same formula is applied to another segment parallel to or at right angles to the first segment.

Actually, it was during the evaluation of numerous combinations of magnitudes and directions of forces and moments with his WeldPAD program, that the author happened to note the sudden variations in the design capacity of parallel and perpendicular segments in weld groups.

Again, in the case of lap joints in which three sides of a flat are welded to a wider plate, the strength according to BS5950 is limited by the parallel strength, denying the user any advantage from the transverse segment. However, Eurocode permits the summation of the individual strengths to be taken at their separate values. (Ref. y)

In many welding specifications and manuals, standard layouts are detailed and relevant parameters tabulated, to optimise welding strength economically and efficiently. As already described, adoption of prequalified welds would be an economical and efficient way of simplifying, if not eliminating the design step.

5.2. Design for Economy and Efficiency

For economy and efficiency, design must take into account fabrication considerations. In addition, the following points must be borne in mind during design stage:

1. Avoid overmatching weld strength with respect to base metal strength, as the joint becomes less ductile and may crack.
2. Avoid biaxial and triaxial stresses at or near welds, extending the connected elements if possible.
3. Avoid abrupt geometric discontinuities at welds, especially under tension loading.
4. Avoid cutting across stress lines with the weld.
5. Orient welds so that contraction strains are imposed on the base metal in the longitudinal (and not transverse) direction, to prevent lamellar overstress.
6. For maximum economy, weld metal volume must be minimum. Furthermore, reducing the weld metal volume reduces the heat input and the resulting shrinkage and distortion. Minimizing the weld metal also minimizes the potential for weld defects.
7. Don't always weld on both sides of a piece just because it can be done. There are many applications where it may be possible to weld on one side of a joint only. For example, the attachment of a column base plate to a column can in many cases be made with fillet welds on one side of each flange and the web.
8. Avoid welding all around. This welding is excessive in most cases. It may even be wrong in some. Welding all around may violate the AISC Specification requirement that welds on opposite sides of a common plane be interrupted at the corner (i.e., when the weld would have to wrap around the corner at an overlap). The weld-all-around symbol should not be used if the entire perimeter of the weld cannot be accessed.

9. Fillet welds are better than groove welds. Fillet welds generally require less weld metal, easier, and more dependable, than groove welds. Further, the use of fillet welds virtually eliminates base metal preparation, which is labour intensive.
10. Longer fillet welds of smaller size are better than shorter lengths of larger size. A 6 mm fillet weld 1 m long has the same capacity as a 12 mm fillet weld 0.5 m long, but has only half the metal volume as the latter. Final decision will involve other considerations of increased weld length (such as size of gusset plates).
11. Keep fillet weld sizes at or below 8 mm (5/16-in.), when possible. As per AWS D1.1, this weld size can be deposited in one pass with the shielded metal arc welding (SMAW) process in the horizontal and flat positions. Larger weld sizes will require multiple passes.
12. Use intermittent fillet welds when possible. Under typical loading, intermittent fillet welds can often be specified and the weld metal volume can be reduced accordingly. However, in applications that involve dynamic loads or fatigue, intermittent fillet welds are not advisable, in fact, not permitted.
13. Recognize the increased strength of transversely loaded fillet welds, as discussed under Code Provisions.
14. Partial penetration groove welds are better than full penetration welds. Partial-joint-penetration groove welds generally require less base metal preparation and weld metal. They also reduce heat input, shrinkage, and distortion. It is sometimes possible to increase plate thickness and use a partial penetration groove weld instead of a full penetration groove weld.
15. Depending upon thickness, a particular combination of root opening and bevel angle will minimize weld metal volume in a groove weld joint.
16. Consider double-sided preparation. In some cases, the additional labour to prepare the surface can be offset by savings in weld metal volume (and labour).
17. Avoid seal welding unless it is required. Seal welding is generally unnecessary, unless the joint is required to be air-tight or water-tight.

6. FABRICATION CONSIDERATIONS

6.1. Choice of Process

Joining materials and processes must be matched unless unavoidable. Table 2 gives suitable combinations, on the basis of a ten-point system, and with following notation:

Rating: 10 = Excellent, 5 = Fair, 1 = Seldom/never used
Notes: * : Heated tool, ** : Hot gas, *** : Induction
Process: **AW** = Arc welding, **OAW** = Oxyacetylene welding, **EBW** = Electron beam welding, **RW** = Resistance welding, **B** = Brazing, **S** = Soldering, **AB** =Adhesive bonding

Table2 : Suitability of Processes for Various Materials

Materials *Process* →	AW	OAW	EBW	RW	B	S	AB
Cast iron	7	10	1	1	3	1	7
Carbon Steel, low-alloy steel	10	10	7	10	10	3	7
Stainless steel	10	7	7	10	10	5	7
Aluminium, Magnesium	7	7	7	7	7	1	10
Copper, Copper alloys	7	7	7	7	10	10	7
Nickel, Nickel alloys	10	7	7	10	10	5	7
Titanium	7	1	7	7	3	1	7
Lead	7	7	1	3	1	10	10
Zinc	7	7	1	3	1	7	10
Thermoplastics	10*	10**	1	7***	1	1	7
Dissimilar metals	3	3	7	3	3-7	N/A	10

6.2. Fabrication for Economy and Efficiency

Many design considerations are based on fabrication considerations. Additionally, the following may be significant:

1. Flat and horizontal positions are better than other positions (Fig. 1). These positions use the base metal and gravity to hold the molten weld pool in place, allowing easier welding, a faster deposition rate, and generally higher weld quality.
2. Avoid welding on galvanized surfaces, particularly in the shop. Special ventilation must be provided in the shop to exhaust the toxic fumes that are produced. Additionally, the galvanizing must commonly be removed by grinding in the area to be welded. This requires the subsequent touching up with cold galvanizing compound after welding and cleaning. All of these operations add cost.
3. Avoid arc strikes and spatter in high stress areas, as these will cause hard spots initiating cracks.
4. Keep electrodes safe from absorbing moisture to avoid introduction of hydrogen into the molten weld pool.
5. Do not weld on wet surfaces, again to avoid entrapping hydrogen.
6. Protect joints to be welded from wetness.
7. Do not artificially cool welded areas by water spray or forced air, as this will lead to brittleness.
8. Protect the work area from wind to avoid diluting or blowing away shielding gases, and losing pre-heat or interpass heat.

6.3. Code Provisions for Fabrication

Codes provide many guidelines and safeguards to maintain quality and safety in weld fabrication. For instance, AWS provides the following formats governing acceptable welds, subject to the welders and operators involved also being suitably qualified:

(a) Welding Procedure Specification (WPS):

WPS is a document with all the variables for a welding operation, made available to the production shop and crew. A section on Procedure Control, referring to critical steps in the production sequence is also included for the planners and supervisors. Appendix A to this paper shows a specimen WPS.

The essential variables to be included are:

(a) Welding process, (b) Joint details, (c) Base metal group,
(d) Filler metal, (e) Position, (f) Pre-heat,
(g) Interpass temperature, (h) Gas, (i) Electrical characteristics, and,
(j) Welding technique details.

The manufacturer or contractor shall prepare a written WPS that specifies all the applicable essential variables.

(b) Procedure Qualification Record (PQR):

PQR is a document containing the specific values for the WPS variables, and serving as written confirmation of a successful WPS qualification.

(c) Methods of Testing and Acceptance Criteria for WPS Qualification:

Details must be provided on the specifications detailing test specimens, non-destructive and destructive tests to be conducted, and the criteria that the results must satisfy.

(d) Prequalification of WPSs:

Prequalified welds, as detailed in tables and figures given in the Code, are exempt from the WPS qualification testing in Item (c) above. Only certain processes, and specified base metal / filler metal combinations are approved for prequalification.

These are subject to stringent pre-heat and interpass temperature requirements, thickness ranges, limitations of WPS variables, and numerous other requirements for various electrodes and types of welds.

Welds made under these conditions would save considerable time and effort, and hence expense in the acceptance process.

7. PERSONNEL

Welders are trained more rigorously, and tested more frequently than in almost any other profession. They must be certified for specific types, positions, and processes of welding before they may be permitted to do the welding.

For welding operators, and tack welders to be certified, AWS requires them to pass welder performance qualification (WPQ) tests, to document their ability to produce sound welds under different specified circumstances.

Specifications cover the number and types of specimens, their thickness, diameter and other dimensions; types of tests and acceptance criteria, separately for each job description.

The document verifying details of the WPQ test is known as "Welder Performance Qualification Record" (WPQR).

The WPQ has to be repeated when critical parameters change, or when a welder's performance comes under question. If the approval is given for a stipulated period, WPQ must be repeated when it lapses.

While manual welding needs considerable skill and concentration, operators of sophisticated automatic and robotic equipment have even more responsibility for initial set-up of and frequent attention to their machines because of the many variables that have to be input and the sensitive controls that have to be exercised.

8. ENVIRONMENT

The ambient temperature, wind, air pollution, humidity, almost everything concerned with the environment and weather at the job site is very critical to good welding. Following are some of the actions that may be required, depending on the existing circumstances:

- Pre-heating and post-heating may have to be carried out by hot air blowers or other means
- Weld tips may have to be cooled by water jackets
- Welding fumes may have to be carried away by exhaust fans
- Draughts may have to be cut down by screens

To produce good welds, every related parameter must be just right, or may vary only within very narrow bands.

9. TYPES AND CLASSIFICATION OF DEFECTS

The quality of welded joints depends on the base metal, weld metal, welding action, and other factors. Considerable potential for defects exist in every step of welding, with human error underlying most of them.

Ricker (1988) states the truism, "Failures in service rarely occur in properly designed and executed welds. Most fractures start at a notch, groove, discontinuity or other type of stress-raiser." This is the reason that weld defects take on more than normal importance.

Some common defects in welding are discontinuities such as porosity or voids, slag inclusions, and cracking. Note that "discontinuity" simply means non-homogeneity of properties, and may not always be a defect. However, all defects result in discontinuities in the weld. Of these, porosity and slag inclusions are tolerable to a certain extent, but cracking is never to be allowed.

9.1. Types of Defects

Common defects are depicted in Fig.2, and described briefly in alphabetical order.

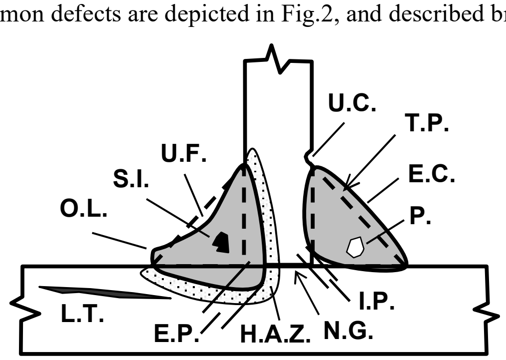

Figure 2 : Weld Defects

E.C. - Excessive Convexity, E.P. – Excessive Penetration, H.A. – Heat Affected Zone (Shown only on one side), I.P. – Insufficient Penetration, L.T. – Lamellar Tearing, N.G. – No Gap, O.L. – Overlap, P. - Porosity, S.I. – Slag Inclusion, T.P. – Theoretical Profile, U.C. – Undercut, U.F. – Under Fill.

(a) ***Excessive Convexity,*** is generally not deleterious to the joint, but it is always a waste of weld metal, adding to the expense. Where appearance or fit is important, the excess is very difficult and time consuming to remove. It also worsens some other problems such as slag inclusions. Under certain adverse combination of circumstances involving thin plates, such excessive deposits may actually weaken the joint.

(b) ***Excessive Penetration*** of the weld into the base metal also results in wasted weld metal, and may burn through thinner parts.

(c) ***Heat Affected Zone Defects,*** including hydrogen-related cracking, and leading to lamellar tearing, can be major problems.

(d) ***Insufficient Penetration*** will reduce the strength of the joint.

(e) ***Lamellar Tearing*** refers to the separation of the base metal into layers due to temperature variations in thick hot rolled sections, especially in the presence of slag inclusions. It destroys the integrity of the joint.

(f) ***No Gap*** or insufficient gap between the connected parts at start results in development of internal tensile stresses in the weld upon cooling, overstressing or destruction of the joint during or even before service.

(g) ***Overlap*** is a spill over of the weld metal, usually on horizontal surfaces, at start or end of welding. It does not add to the strength, and is waste of metal.

(h) ***Porosity,*** referring to void inclusions, is the collection of air or gas pockets due to weld torch spluttering or sudden uneven movement of weld tip during welding. Voids weaken the weld and cause stress concentration.

(i) ***Slag Inclusion*** occurs due to uneven welding and incompatibility of weld metal and base metal. Slag inclusions weaken the weld and cause stress concentration.

(j) ***Undercut*** is the burning off of the base metal at the weld edge due to excessive temperature, and/or due to slow or stopped movement of the weld torch. It gives rise to stress concentrations and damage to the base metal, sometimes to the extent that the undercut part becomes unserviceable.

(k) ***Under Fill*** refers to the concavity of the fillet weld face.

9.2. General Causes and Consequences of Defects

General causes of defects are the following:

- Adverse or incompatible base metal and/or filer metal properties
- Unsuitable process characteristics
- Harsh environmental conditions
- Improper joint design, preparation, alignment, or fit-up
- Inefficient workmanship (which must not be tolerated)

All defects contribute to the following outcomes, with further adverse consequences:

- Points of stress concentration
- Degradation of material properties such as ductility and toughness
- Reduction of load-bearing cross-sectional area
- Adverse effects on long-term characteristics of the base metal

To eliminate these defects, the causes mentioned must be guarded against, and the planning, preparation, welding, and subsequent cooling procedures must be carefully and continually monitored.

In addition to the process, the materials used and the parameters of the electric power, electrodes and other materials involved also must be evaluated in an integrated manner.

Repair procedures must be established and pre-qualified, according to code requirements.

9.3. Classification of Defects

Defects may not be confined to the weld metal alone, but may extend for a certain distance into the base metal surrounding the weld, known as the "Heat Affected Zone" (HAZ), in which the microstructure (metallurgical) and physical properties of the base metal are altered during and due to the process of welding (Figs. 2, 3.)

Defects may be generally classified according to location as listed in Table 3.

Table 3 : Classification of Defects by Location

Location	***Defect***	***Cause***

Fusion Zone	Porosity	Dissolved gases released upon solidification
	Slag and other electrode inclusions	Welding process, often unavoidable • Contamination by non-consumable electrodes
	Hot cracks	Shrinkage stresses at boundaries of low melting particles
	Cold cracks	Hydrogen embrittlement
	Severe large-scale segregation	Highly dissimilar base metals • Unmatched base metals and fillers
HAZ	Cold cracks	Hydrogen diffusion • Unfavourable chemical composition
	Lamellar tears in base metal	High tensile stresses in the through-thickness direction from: (a) Rolled base metal; (b) Deposition of large amounts of filler metal; and, (c) High degree of restraint
	Other cracks	Liquation, re-heat, strain aging, stress corrosion, weld decay, etc.
Joint related	Porosity	Entrapped air • Volatile contaminants
	Excessive distortion	Unbalanced sizes • Excessive heat input
	Severe dilution	Improper design • Unsuited process
	Incomplete penetration	Improper design • Unsuited process or parameters
	Surface offset or mismatch	Misalignment of joint components
	Voids or cracks	Shrinkage, poor fit-up, and/or excessive restraint
	Underfill	Poor fit

10. CRACKING CONTROL

10.1. Types of Cracks

Even before any loads are placed on a welded joint, cracks may occur inside the weld due to solidification and sudden cooling of large deposits in a single pass, and weld shrinkage stresses.

Weld related cracking occurs at or soon after fabrication.

Cracking is never permitted under any circumstances. Cracks may appear under different conditions and in different locations, as shown in Fig. 3.

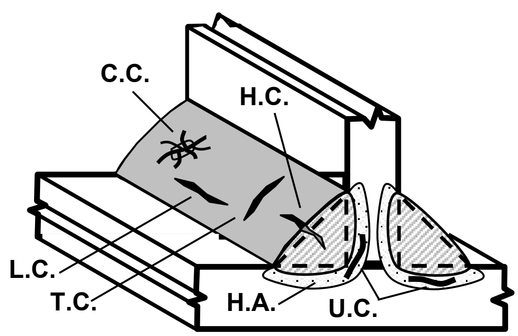

Figure 3 : Types of Cracks

C.C. – Crater Crack, H.A. – Heat Affected Zone, H.C. – Throat Crack, L.C. – Longitudinal Crack, T.C. – Transverse Crack, U.C. – Underbead Crack.

(a) ***Centreline Crack:*** Named thus because of its occurrence along the centre line of a weld bead. It may be induced by: (i) Segregation, (ii) Bead-shape, or, (iii) Surface-profile

(b) ***Cold Cracks:*** Those occurring after cooling, generally related to hydrogen interaction. Most cold cracking originate from shrinkage strains, which are higher for the larger weld sizes, deeper penetrations, and higher strength base and/or weld metals.

(c) ***Crater Crack:*** Radial cracks and metal tearing formed in weld craters as the weld pool solidifies and shrinks.

(d) ***Face Crack:*** A crack that appears on the face of weld or on the crown bead (that is the topmost bead in a multiple pass weld), which runs either parallel with (i.e. longitudinal) or perpendicular (i.e. transverse) to the direction of welding.

(e) ***Heat-Affected Zone Crack:*** A crack in the heat-affected zone (HAZ) of the weldment. This is not exactly weld cracking, but cracking of the base metal due to welding, mainly related to hydrogen. This is also called "Cold Cracking", "Underbead Cracking", "Toe Cracking", or "Delayed Cracking".

(f) ***Hot Crack:*** Those occurring at high temperatures during fabrication, caused by solidification.

(g) ***Lamellar Tear:*** A subsurface terrace and step-like crack in the base metal with a basic orientation parallel to the wrought surface caused by tensile stresses in the through-thickness direction of rolled base metal weakened by the presence of small dispersed, planar shaped, non-metallic inclusions parallel to the metal surface.

(h) ***Longitudinal Crack:*** A crack with its major axis orientation approximately parallel to the weld axis. It is a face crack.

(i) ***Root Crack:*** A crack on the exposed surface of a weld apposite the side from which welding was done.

(j) ***Toe Crack:*** A crack on the junction of the weld face and the base metal. It is a HAZ crack.

(k) ***Transverse Crack:*** A crack with its major axis oriented approximately perpendicular to the weld axis. It is a face crack. Also called "Cross Crack", this is not very common.

(l) ***Underbead Crack:*** A crack within the heat-affected zone generally not extending to the surface of the base metal. It is a HAZ crack.

(m) ***Weld Metal Crack:*** A crack in the metal in a fusion weld consisting of that portion of the base metal and filler metal melted during welding.

10.2. General Causes and Remedies of Cracking

Any crack is unacceptable, regardless of location or size. When a crack is detected, after welding, or after cooling, it must be immediately reported to the supervisor and remedial measures must be undertaken.

The usual repair for cracks is to remove all metal around the crack, for about 50 mm beyond each end of the crack, start the chipping from the ends and work towards the middle, and then prepare the weld surface afresh and re-weld. Crater crack surfaces must be cleaned and prepared, then re-welded.

Weld cracking with mild steel is seldom a problem in material less than about 10 mm. thick. With thicker material, welds are subjected to rapid cooling rates, which frequently induce high stresses and lead to cracking. Low ambient temperature increases the cooling rate and produces a similar effect.

Constrained shapes not free to flex or deflect under thermal stresses also have a tendency to crack, as do steels of high hardenability or "hot-shortness".

Some of the common causes of cracking and remedies therefor (with the exception of HAZ cracking which is treated separately) are listed in Table 4.

Table 4 : Causes and Remedies for General Cracking

Crack Type	***Possible Cause***	***Recommended Remedy***
General Cracks	1. Joints are too rigid	1. Eliminate rigid joints by proper design
	2. Welds are much smaller than the parts joined	2. Increase weld size • Make full size weld in shorter lengths
	3. Joints highly restrained	3. In-process stress relief by peening (that is, cold hammering or shot blasting of weld surface)
	4. (a) Joints insufficiently prepared; (b)Weld workmanship poor; (c) Electrode unsuitable; etc.	4. Avoid by: Prior planning and checking; appropriate and frequent inspection; proper fusion; pre-heating.
Centreline Crack, Segregation induced	Separation of low melting-point constituents such as copper, phosphorous, sulphur, or zinc compounds in the base metal.	(a) Limit weld penetration (b) Provide a "buttering" interface layer of weld material through a low-energy process such as SMAW (c) In the case of sulphur, use filler materials with high levels of manganese to convert it to manganese sulphide which has a high melting point

Centreline Crack, Bead-shape induced	Deep penetrating processes such as SAW and carbon-dioxide shielded FCAW	(a) Design weld to be wider (10% to 40% more) than it is deep (b) Reduce penetration with lower amperages and larger diameter electrodes
Centreline Crack, Surface-profile induced	Concavity of weld surfaces that usually arise from: (a) High arc voltages (b) Fast travel speeds (c) Vertical downward welding	Promote convexity of weld by: (a) Lower arc voltages (b) Slower travel speeds (c) Vertical upward welding
Crater Crack	Shrinkage due to low melting constituents segregating in the weld pool during solidification	(a) Allow arc to stay longer at the crater; (b) Use GTAW or other technique to slow down solidification
Transverse Crack	Longitudinal residual stress due to weld metal of higher strength than base metal, compounded by HAZ cracking factors	(a) Adopt low hydrogen practice (*See* HAZ cracking); (b) Reduce weld metal strength, consistent with required joint strength

Table 4 : Causes and Remedies for General Cracking (Contd.)

Crack Type	***Possible Cause***	***Recommended Remedy***
Hot Crack	Shrinkage stresses produced during solidification become concentrated in a small liquid region, mainly due to presence of low-melting alloy sulphides or (in some ferrous alloys) silicates	Control both the amount and type of sulphides that form, and the minor alloy constituents that may promote such cracking

Careful attention must be paid to the following factors to avoid cracking:

1. Welding sequence
2. Pre-heat and interpass temperatures
3. Post-weld heat treatment
4. Joint design
5. Welding procedure
6. Filler material

As cracking must be prevented at all costs, some of the more significant types will be discussed in greater detail in the sections to follow.

10.3. Cracking in Fillet Welds

Cracking is more common in fillet welds than in groove welds because both legs of a fillet joint are rigidly fixed. This rigidity prevents deflections that normally absorb thermal stresses.

Some factors influencing crack development in fillet welds, and their alleviation are as follows:

(a) Gap: For workpieces more than about 25 mm thick, a gap of 0.8 mm to 1.6 mm should be left to allow the weld to shrink during cooling. Shrinkage stresses may be minimised by grooving the plate edges or inserting a compressible material between the workpieces.

(b) Polarity: Positive polarity is to be preferred for fillet welds to obtain greatest penetration and minimum tendency for porosity at high speeds.

But, if chemical composition of workpiece promotes cracking, negative polarity should be used to reduce penetration and minimize admixture with base metal. The negative polarity also increases the melt-off rate by 20 to 30%, helping to build up a good bead with the preferred convex shape.

(c) Bead Shape: Concavity and depths larger than widths must be avoided. Deep beads also make slag removal difficult.

(d) Electrode Size: Large diameter electrodes reduce penetration and decrease admixture with the parent plate, thus reducing cracking.

(e) ***Flux Coverage:*** Flux thickness should be just sufficient to cover the arc.

(f) ***Number of Arcs:*** In comparison with a single arc, twin electrodes, frequently used on flat fillets, produce benefits against porosity and cracking for a given speed, namely: (i) Less penetration, (ii) Less admixture, (iii) More melt-off, and, (iv) Less arc blow.

(g) ***Type of First Pass:*** A manual first pass with an E7018 electrode yields the following benefits against cracking: (i) Reduces admixture, and, (ii) Assurance against melt-through under poor fit-up conditions

(h) ***Edge Preparation:*** The following steps will minimise internal cracking and slag inclusions:

(i) Prepared angle on single-pass welds should not be too acute.

(ii) Bevel joints should not have included angles of less than at least 60°, or width smaller than the depth.

(iii) For 100% penetration T-joints on heavy plates, the first pass on each side should be made with E7018 electrode.

Alternatively, the joint should be prepared in such a manner as to avoid excessive penetration resulting in beads having greater depth than width.

(i) ***Angle of Electrode:*** When two steels to be welded are of different chemical compositions, arc movement should be toward the more weldable alloy to minimize adverse admixture.

(j) ***Electrode Stick-out:*** Larger electrical stick-out (distance from point of electrical contact to electrode tip) increases melt-off rate and decreases penetration and admixture, thus reducing cracking tendencies. However, the bead shape is more difficult to control.

(k) ***Grounding:*** The workpiece should be normally grounded at the “start” end of the weld. However, on short welds, both ends of the joint should be grounded.

(l) ***Speed and Current:*** For steels with higher proportion of carbon and other alloy constituents, travel speed and welding current should be decreased, to reduce penetration and minimise the size of the molten puddle, thus avoiding cracking.

10.4. Weld Metal Cracking

Cracking in the weld metal is a serious matter affecting the very basis of the joining process, and requires careful attention to detail at all levels.

Table 5, reproduced with permission from *Structural Welding Quality Handbook* (Ref. 27), lists the principal causes and remedies.

Table 5 : Causes and Remedies for Weld Metal Cracking

Possible Cause	***Recommended Remedy***
High joint rigidity	Pre-heat to reduce magnitude of residual stresses • Minimise shrinkage stresses using backstep of block welding sequences • Relieve residual stresses mechanically or with heat
High weld depth-to-width ratio	Increase arc voltage, decrease the current, or both, to widen the weld bead or decrease the penetration
Improper joint design	Maintain proper groove dimensions to allow deposition of weld cross-section to overcome restraint conditions
Defective electrodes	Change to new electrode; bake electrodes to remove moisture • Store and maintain electrodes in a clean, dry area • Protect electrodes from excessive exposure to dirt and grime when in use
Excessive dilution of weld metal	Decrease voltage • Decrease current/wire feed speed • Increase travel speed • Use DC (–) polarity if permitted
Small weld bead fillet welds and groove root passes	Increase size of weld deposit
Shrinkage and distortion	Reduce either current or voltage, or both • Increase travel speed • Use balanced welding on both sides of joint • Reduce groove angle
Poor fit-up	Use correct root opening

Crater cracking	Fill crater before extinguishing the arc • Use back-stepping technique • Use welding current decay device when terminating the weld bead
High sulphur steel	Use filler metal low in sulphur

10.5. HAZ Cracking

Elimination of HAZ cracking needs special attention. Table 6 from Ref. 27 lists the principal causes and remedies.

Table 6 : Causes and Remedies for HAZ Cracking

Possible Cause	*Recommended Remedy*
High hydrogen level, from moisture or organic compounds in steel, electrode, or shielding gas, and atmospheric humidity	All materials must be clean and dry • Consumable materials must be stored, maintained, and handled properly • Post-weld heat treatment in high hydrogen levels
Hydrogen embrittlement	Use clean electrode • Use dry shielding gas • Remove contaminants and moisture from the steel surface • Hold weld at elevated temperature before cooling to diffuse hydrogen
Material microstructure highly sensitive	Reduce weld cooling rate by pre-heating surrounding steel
High residual or applied stress	Redesign the joint or assembly • Revise welding sequence • Apply intermediate stress-relief treatment, either mechanically, or by thermal stress relief by pre-heating or post-heating, where practical and economical • Shore up the structure temporarily
Overmatching filler metal	Use matching or under matching filler metal, when permitted
Excessive pre-heat of interpass temperature, causing a coarse-grained HAZ	Reduce excessive pre-heat • Allow adequate cooling between passes to reduce excessive interpass temperature
Heat hardenability steel (high carbon or poor steel composition)	Pre-heat • Post-heat immediately upon weld completion • Decrease penetration by using small electrodes and heat input • Use low-hydrogen electrodes
Hot cracking	Use low heat input • Deposit thin layers
Low ductility	Pre-heat

11. CONTROL OF OTHER DEFECTS

11.1. Porosity

Porosity refers to the voids formed by gases released and trapped in the molten weld metal during the solidification of a weld.

The gases are mainly hydrogen, and to a smaller extent carbon monoxide, carbon dioxide, hydrogen sulphide, nitrogen, oxygen, and water vapour. Porosity reduces weld strength.

Porosity may be classified as:

(a) Piping Porosity, namely tubular shaped voids perpendicular to the surface of the weld, called “pin holes” when visible at the surface. Visible piping porosity is not permitted in complete joint penetration groove welds in butt joints transverse to the direction of tensile stress. However, limited piping is acceptable in other butt joints and fillet welds.

(b) Sub-surface Porosity, due to trapped gases below the surface, acceptable to a limited extent.

Table 7, taken from Ref. 27 lists possible causes of porosity and recommendations for their avoidance.

Table 7 : Causes and Remedies for Porosity

Possible Cause	***Recommended Remedy***
Electrode contamination	Store and maintain electrodes in a clean, dry area • Protect electrodes from excessive exposure to dirt and grime when in use
Excessive moisture in electrode covering on joint surfaces	Use recommended procedures for drying and storing electrodes
Wind and drafts	Protect weld region from wind and drafts • Reduce fume exhaust system flow rate
Moisture on joint surface	Use pre-heat
Workpiece contamination	Remove all grease, oil, moisture, rust, paint, and dirt, from work surface before welding • Use filler metals high in deoxidisers
High sulphur steel	Use electrodes with basic slagging reactions
Rapid solidification rate	Use pre-heat • Increase welding heat input
Excessive hydrogen, nitrogen, or oxygen in welding atmosphere	Use low-hydrogen welding processes • Use filler metals high in deoxidisers • Increase shielding gas flow rate
Inadequate shielding gas coverage	Eliminate drafts blowing into the welding arc • Increase gas flow rate • Decrease excessive gas flow to avoid turbulence in the weld zone
Gas contamination	Verify use of welding grade shielding gas • Check for leaks in supply system
Excess contact tube-to-work distance	Reduce stick-out
Arc voltage too high	Reduce voltage

In AWS Code, individual holes not greater than about 0.8 mm are permitted, the total lengths being limited to about 10 mm in any 25 mm length of weld and to about 20 mm in 300 mm length.

Beyond these limits, the recommended repair for voids is to remove the unacceptable portions and re-weld.

11.2. Slag Inclusions

Inclusions in welding are a direct consequence of the electrodes that are used in welding to supply the following to the welding site:

1. Filler material and alloys
2. Flux with gas and slag producing agents
3. Non-metallic solid particles produced welding
4. Current conducting accessories

Many of these agents are introduced for specific purposes such as alloying, contaminant shielding, etc. and hence cannot be eliminated from the welding process. They are designed also to be self-eliminating, as for instance slag that rises to the top of weld pool.

Care must be taken to eliminate the residues that would be entrapped in the weld pool and weaken the weld.

Common causes of and remedies for slag inclusions, adapted from Ref. 27 are listed in Table 8.

Table 8 : Causes and Remedies for Slag Inclusions

Possible Cause	***Recommended Remedy***
Incomplete interpass slag removal	Remove slag between passes
Too wide a weaving motion	Use stringer passes • Reduce width of weaving technique
Too large an electrode	Use a smaller electrode size for better access to joint

Improper joint design	Increase groove angle of joint
Erratic travel speed	Use a uniform travel speed

Table 8 : Causes and Remedies for Slag Inclusions (Contd.)

Possible Cause	*Recommended Remedy*
Slag flooding ahead of the welding arc	Reposition work to prevent loss of slag control • Change electrode or flux to improve slag control • Increase travel speed • Change electrode angles • Reduce arc length
Entrapped pieces of electrode covering	Use undamaged electrodes
Oxide inclusions	Provide proper gas shielding

Debris from tungsten and other non-consumable electrodes must be carefully removed, especially when starting and nearing the end of the electrode.

The recommended repair for slag inclusions is to remove the unacceptable portions and re-weld.

11.3. Overlap

Table 9 lists causes and remedies for overlap.

Table 9 : Causes and Remedies for Overlap

Possible Cause	*Recommended Remedy*
Low travel speed	Increase travel speed
Low welding current	Increase current and/or wire feed speed
Large weld size	Use smaller electrode • Increase travel speed
Incorrect electrode angle	Adjust electrode angle such that arc does not push molten puddle over unmelted regions

The recommended repair for overlap is to remove the excess weld metal, taking care not to introduce fresh defects.

11.4. Undercut

Table 10 lists causes and remedies for undercut.

Table 10 : Causes and Remedies for Undercut

Possible Cause	*Recommended Remedy*
Travel speed too high	Reduce travel speed
Welding voltage too high	Reduce voltage
Welding current too high	Reduce current • Reduce wire feed speed • Use proper welding current for electrode size and welding position
Too long an arc length	Reduce arc length
Incorrect electrode angles	Use proper electrode angles
Insufficient dwell	When using a weaving technique pause at each side of the weld bead
Arc blow	Adjust location of ground connection • Use two or more ground connections • Reduce arc length • Weld in the direction that the arc blows • Use AC polarity • Reduce current

The recommended repair for undercut is to prepare the surface, and deposit additional weld metal to acceptable shape and size.

11.5. Spatter

Table 11 lists causes and remedies for spatter, which is more an appearance factor than a strength problem.

Table 11 : Causes and Remedies for Spatter

Possible Cause	***Recommended Remedy***
Welding current too high	Reduce welding current
Too long an arc length	Reduce arc length
Arc blow	Adjust location of ground connection • Use two or more ground connections • Reduce arc length • Weld in the direction that the arc blows • Use AC polarity • Reduce current
Wet, dirty, or damaged electrode	Properly maintain and store electrodes

The recommended repair for spatter, if deemed necessary, is to chip and grind the surface smooth.

11.6. Incomplete Fusion

Table 12 lists causes and remedies for incomplete fusion.

Table 12 : Causes and Remedies for Incomplete Fusion

Possible Cause	***Recommended Remedy***
Insufficient heat input	Follow welding procedure specification • Increase arc voltage • Increase current/wire feed speed • Reduce travel speed
Incorrect electrode angles	Maintain proper electrode angles
Improper weld technique	When using a weaving technique, dwell momentarily on the side walls of groove • Keep electrode directed at the leading edge of puddle
Too large a weld puddle	Minimise weaving for better control • Increase the travel speed
Weld metal running ahead of the arc	Reposition work • Reduce current • Increase weld travel speed
Trapped oxides or slag on weld groove or weld face	Clean weld surface prior to welding • (Also *see* Slag Inclusions)
Arc blow	Adjust location of ground connection • Use two or more ground connections • Reduce arc length • Weld in the direction that the arc blows • Use AC polarity • Reduce current
Inadequate gas shielding	Increase flow rate • Reduce electrode extension
Improper joint design	Use groove angle and root opening with adequate access to bottom of the groove and sidewalls • Use smaller electrode • Use proper electrode extension

Recommended repair for incomplete fusion is to remove affected portions and re-weld.

11.7. Incomplete Joint Penetration

Table 13 lists causes and remedies for incomplete joint penetration.

Table 13 : Causes and Remedies for Incomplete Joint Penetration

Possible Cause	***Recommended Remedy***
Insufficient root opening • Insufficient groove angle • Excessively thick root face	Use proper joint geometry
Bridging of root opening	Use wider root opening • Use smaller electrode in root pass
Failure to backgouge when specified	Backgouge to sound metal when required

Table 13 : Causes and Remedies for Incomplete Joint Penetration (Contd.)

Possible Cause	***Recommended Remedy***
Improper weld technique	Maintain electrode angle normal to work surface to achieve maximum penetration • Keep arc on leading edge of puddle • Decrease arc length • Check electrode polarity

Slag flooding ahead of welding arc	Adjust electrode or work position • Reposition work to prevent loss of slag control • Change electrode or flux to improve slag control • Increase travel speed • Change electrode angle • Reduce arc length
Insufficient heat input	Follow welding procedure specification • Increase voltage • Increase current/wire feed speed • Reduce travel speed

The recommended repair for incomplete joint penetration is to remove the existing weld metal or backing as required, to expose the portion of the root requiring weld, then prepare the surface and deposit fresh weld.

11.8 Miscellaneous Controls

(a) ***Underrun:*** If the weld size is less than the design dimensions to within a specified underrun (approximately 30% to 50%), the surface may be prepared afresh and additional weld may be deposited.

(b) ***Convexity:*** If the convexity of the weld or the final beads of a multi-pass weld is more than stipulated criteria (approximately 20%), the excess weld metal may be removed without introducing fresh discontinuities.

(c) ***Concavity:*** If the concavity reduces the throat below the design value, additional weld metal must be deposited.

12. SHRINKAGE AND DISTORTION CONTROL

12.1. Causes and Types

Welding causes distortion because the heated regions are restrained by the rest of the steel as they cool and contract. Under extreme circumstances, a structural member could be distorted so severely that straightening of the member would be required, particularly in an application that involves architecturally exposed structural steel, with the resultant increase in cost.

The potential for distortion frequently can be reduced through proper selection of the connection configuration and joint details at the design stage. The fabricator may be fruitfully involved in the redesign.

Non-uniform expansion from heating and contraction due to cooling of the weld metal and base metal during and after welding causes internal tensile stresses of nearly the same magnitude as the yield strength of the weld metal develop in the joint.

As the joint cools and any external restraint (imposed for welding purposes) is released, the internal (residual) stresses locked into the weld metal cause distortion, generally evidenced as linear or transverse shrinkage of the entire part, or angular distortion (bending) of the stressed portion of the joint, until the internal stresses balance each other.

In addition, the base metal also experiences differential heating and cooling due to the high temperatures at the arc and the much lower temperatures in the surrounding regions. The large size of the joined workpieces relative to the weld, plus any clamping restraint during welding, again result in the development of internal residual stresses which tend to warp the workpieces.

Some illustrations of the combined effects of weld metal and base metal distortion are shown in Fig. 4. In the figure, broken lines represent the original configuration, and full lines the distorted configuration after the welds have shrunk upon cooling and release of restraints. The remedies should aim at the reduction of contraction forces.

(a) ***Transverse Distortion:*** When the weld is doubly symmetric as in the groove (butt) weld shown, the workpiece contracts in its plane, reducing the lateral dimension.

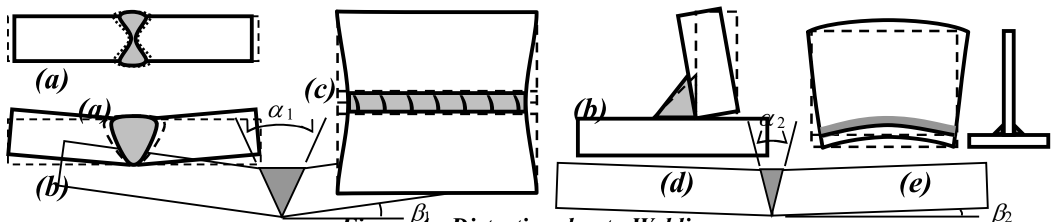

Figure 4 : Distortion due to Welding

Figure 6 : Decrease in Distortion by Reducing Bevel Angle

(b) Angular Distortion: When the weld is unsymmetrical or singly symmetric, the differential shrinkage of the weld causes the connected elements to move relatively in an angular direction, out of the original plane.

(c) Longitudinal Distortion: Longitudinal shrinkage of the weld pulls the adjacent portions of the workpieces along with it while their farther regions remain relatively unaffected.

(d) Distortion from Unsymmetrical Fillet Welding: If fillet welding is done only on one side of a plate in a perpendicular joint, or if the welds are considerably different on the two sides, the uneven shrinkage of the unsymmetrical fillet weld will cause the outstanding workpiece to rotate out of plane.

(e) Bending Distortion: When a longitudinal weld connecting two perpendicular workpieces does not happen to be at the neutral axis of the combination, the weld shrinkage causes an arching of the joint on the side of the neutral axis.

Welding causes distortion because the heated regions are restrained by the rest of the steel as they cool and contract. Under extreme circumstances, a structural member could be distorted so severely that straightening of the member would be required, particularly in an application that involves architecturally exposed structural steel, with the resultant increase in cost. The potential for distortion frequently can be reduced through proper selection of the connection configuration and joint details. The fabricator may be fruitfully involved in the redesign.

12.2. Remedies in Design

Anticipating warping due to welding, designers may eliminate or considerably reduce undesirable shrinkage distortion by designing the welded joints suitably. Many of the economy and efficiency considerations discussed under design would have benefits in this regard. Some additional options are the following:

1. Many codes recommend that weld segments be so arranged that their centroid coincides with the line of application of the force.

   A case in a point is the welding of a single angle to a gusset plate as in Fig. 5, with the weld length along the back of the angle being longer than the weld length along the toe of the attached leg, such that the centroid (G) of the weld group coincides with the projection of the centroid of the angle along which the

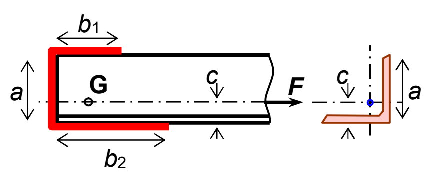

Figure 5 : Unsymmetrical Weld for Angle

   load is applied.

2. Place welds near the neutral axis of bending members
3. Avoid excess weld metal and minimising the volume of the joint by one or more of the following steps as applicable:
   (a) Use double V rather than single V
   (b) Use J or bevel shapes rather than U or V shapes
   (c) Decrease bevel to 15° with a wide root opening and backing plate, or to 30° with a narrow root opening. Effect of a smaller bevel angle is illustrated in Fig. 6. As bevel angle α_2 is smaller than α_1, the distortion angle β_2 is smaller than β_1.

(d) Use intermittent welds rather than continuous welds

(e) In fillet welds, use smaller size welds of longer length

(f) In groove welds, use the minimum root opening and groove angle permitted

4. Beware of weld details and restraints that are likely to cause distortion as the welds cool and shrink.

12.3. Remedies in Fabrication

Many of the economy and efficiency considerations discussed under fabrication would have benefits in this regard. Some additional precautions and compensating steps that may be adopted are as follows:

1. Use as low strength consumables as design permits.
2. Avoid excess weld metal during fabrication by:
   (a) Keeping convexity and over welding to the minimum
   (b) Controlling fit-up
   (c) Using fewer passes to build up a large weld
3. Avoid stops and starts at corners.
4. Balance multiple pass welds on opposite faces of a double weld as depicted in Fig. 7.

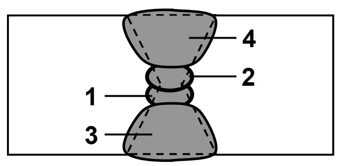

Figure 7 : Balancing Multi-pass Welds

5. Balance multiple bead intermittent welds on opposite sides of a web on to a flange as depicted in Fig. 8.

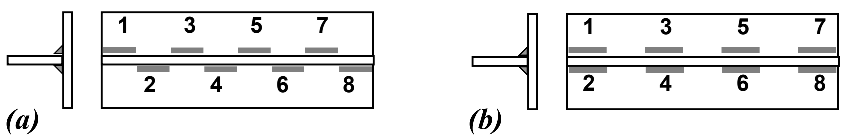

Figure 8 : Balancing Intermittent Welds

6. Sequence subassemblies and final assemblies so that the welds continually balance each other about the neutral axis of the section. (Fig. 9.)
7. Weld from the centre of the member length toward the unrestrained ends of the member, as illustrated in Fig. 9.
8. Back-step the weld in manual welding, that is, for a weld going from left to right, deposit each portion of the weld from right to left. In Fig. 9, back-stepping will imply opposite to the direction of the arrows marked, within each segment.

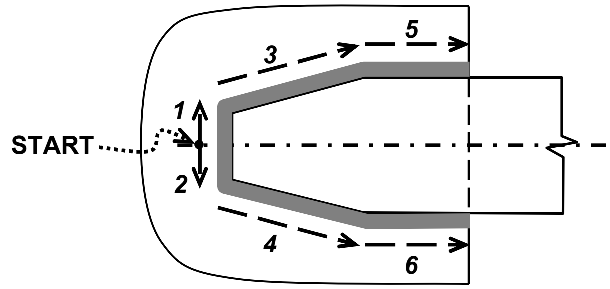

Figure 9 : Starting from Centre and Balancing Welding

9. Weld those joints that contract the most, first in the welding sequence.
10. Weld the more flexible sections first, then straighten, if necessary, before final assembly.
11. Maintain alignment of plates during welding with jigs, or by welding small clip angles and wedges.
12. Pre-bend or otherwise distort the workpiece in the direction opposite to the expected distortion of welding.
13. Clamp workpieces for welding until completely cooled. Clamp two similar members back to back, with some pre-bending if necessary.
14. Heat and cool the weldment in a controlled fashion. Pre-heating can be used to offset expected distortion. Post-weld heat treatment can reduce the residual stresses in structural steels by 80-90%.
15. Reduce welding time, thus decreasing the volume of metal affected by the welding heat.
16. Reduce base metal distortion due to differential heating by increasing the speed of welding by an appropriate process wherever possible.
17. Arrange fitting and welding sequence so that parts can move in one or more directions as long as possible.
18. Weld the more flexible sections together first, so that they may be easily straightened before final assembly.
19. Peen the weld, that is mechanically hammer it to relieve it of residual stress. However, peening is not always practical, and is also not permitted in root welds and final passes, as it may cover cracks and prevent their discovery during inspection or testing.
20. Do not over weld.
21. When an undersized weld is discovered, consider that AWS D1.1 allows a 1/16-in. (6 mm) undersize to remain if it occupies less than 10% of the weld length. This recognizes that an attempted repair may create a worse condition than the undersized weld.
22. Monitor interpass temperatures in welded joints. For a given level of heat input, the interpass temperature in a weldment is largely dependent upon the cross-sectional area of the element(s) being welded. The larger the area, the faster the heat will be drawn from the weldment. As a rule of thumb, if the cross-sectional area of the weld is equal to or greater than 40 in.^{2} (about 260 cm^2), or, is equal to or less than 20 in.^{2} (about 130 cm^2), interpass temperature should be monitored.

13. INSPECTION AND TESTING

More than in any other mode of connection between any other two materials, welding between metals demands careful inspection.

Unless a weld is pre-qualified, it has to be thoroughly inspected, tested if necessary, and certified to be correct. If it is found to be deficient in any spot in any way, corrective measures must be taken, and then it must be re-checked and re-approved.

Inspection must be continuous, starting from before welding and continuing during welding and after welding. The test methods are non-destructive, except for pre-qualified joints where various destructive tests are conducted.

13.1. Non-Destructive Testing

Non-Destructive testing (NDT) may be classified as follows:

- Visual Testing
- Penetrant Testing
- Magnetic Particle Testing
- Radiographic Testing
- Ultrasonic Testing

Visual checking is the simplest and most critical, overall. Apart from cleanliness of joint, which must be maintained from start to finish of welding, visual inspection must cover the following features during one or more phases:

(a) Before Welding:

Groove weld: (i) included angle, (ii) root opening, (iii) root face, and, (iv) alignment.

(b) During Welding:

(i) Electrode type and size, (ii) Welding current and polarity, (iii) Tack welds,
(iv) Fusion, (v) Pre-heat and interpass temperature, (vi) Sequence of passes,
(vii) Travel speed, (viii) Tilt of crater in vertical welding, (ix) Filled craters,

(x) Absence of overlap, (xi) Absence of excessive undercut, (xii) Absence of cracks, and,
(xiii) Slight reinforcement on groove welds

(c) After Welding:

(i) Fusion, (ii) Filled craters, (iii) Absence of overlap,

(iv) Absence of cracks, (v) Absence of excessive undercut, (vi) Full size on fillet welds, and,
(vii) Slight reinforcement on groove welds,

In the other methods of testing, the equipment, consumables, and testing personnel must fulfil the highest quality criteria. Proper interpretation of results is critical.

13.2. Destructive Testing

Destructive testing involves cutting out coupons from the weld joint or within the weld itself, and testing them for hardness, tensile strength, bending, fatigue, micrographic examination, etc.

14. SAFETY CONSIDERATIONS

There are more dangers to personnel in welding than in many other fabrication methods.

Some of the common ones are:

1. Damage to, even loss of, eye sight, upon viewing the weld arc
2. Burns due to hot metal spatter, hot gases, fire, etc.
3. Electrical shock due to short circuit, bad wiring, or careless handling
4. Suffocation, lung damage, unconsciousness, even death, due to noxious gases
5. Bach ache, muscle sprain, etc. from the constant hunched position of the welder
6. Dangers of falls, and other construction accidents, aggravated by the specialised nature of welding

Strict adherence to safety rules and personal protective equipment such as protective clothing, helmet, goggles (of the right density), gloves, etc. must be enforced. Warning signs must be displayed.

Equally important is the danger to the other workers and members of the public who happen to see the arc accidentally, to prevent which, shielding screens must be placed around the welding area. Exhaust fumes must be thrown out well beyond accidental reach of others in the area.

Fire too is a distinct possibility, and fire-fighting equipment and procedures must be in place for emergency use.

15. CONCLUSION

In the preceding sections the various factors and causes that may lead to inefficient and unsafe welds have been described in detail. Measures to avoid deficiencies and remedies to correct defects have been detailed. Steps to safeguard and promote good welding have been listed at various levels of planning, design, fabrication, and testing of welds.

If such guidelines and specifications are adhered to in a professional manner, good welding will become the norm.

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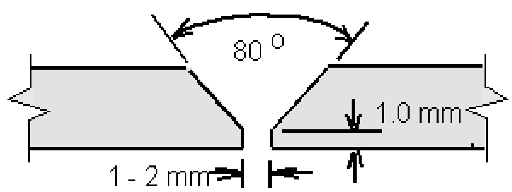
APPENDIX A :: Specimen Welding Procedure Specification

Weld Procedure Number	30 P1 TIG 01 Issue A
Qualifying Welding Procedure (WPAR)	WP T17/A

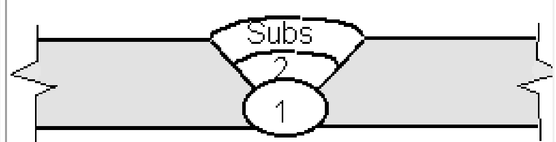
Manufacturer:	*(Name and Address are removed to preserve anonymity – Author)*
Location:	Workshop
Welding Process:	Manual TIG
Joint Type:	Single Sided Butt Weld

Method of Preparation & Cleaning:	Machine and Degrease
Parent Metal Specification:	Grade 304L Stainless Steel
Parent Metal Thickness	3 to 8mm Wall
Pipe Outside Diameter	25 to 100mm
Welding Position:	All Positions
Welding Progression:	Upwards

Joint Design



Welding Sequence



Run	Process	Size Of Filler Metal	Current A	Voltage V	Type Of Current/Polarity	Wire Feed Speed	Travel Speed	Heat Input
1 2 & Subs	TIG TIG	1.2mm 1.6mm	70 - 90 80 - 140	N/A	DC- DC-	N/A	N/A	N/A

Welding Consumables

Type, Designation Trade Name:	BS 2901 Part 2 : 308S92
Any Special Baking/Drying:	No
Gas Flux:	Argon 99.99% Purity
Gas Flow Rate - Shield:	8 - 12 LPM
- Backing:	5 LPM
Tungsten Electrode Type/ Size:	2% Thoriated 2.4 mm dia
Back Gouging/Backing:	Gas Backing
Pre-heat Temperature:	5°C Min
Interpass temperature:	200°C Max

Post Weld Heat Treatment

Time, temperature, method:	Not Required

Production Sequence

1. Clean weld and 25mm borders to bright metal using approved solvent.
2. Position items to be welded ensuring good fit-up; apply purge
3. Tack weld parts together by TIG, tacks at least 5mm min length
4. Deposit root run using 1.2mm dia. wire
5. Inspect root run internally
6. Complete weld using 1.6mm dia wire using stringer beads as required.
7. 100% Visual inspection of completed weld