THE ORIGIN, SIGNIFICANCE AND PREVENTION OF DEFECTS IN WELDS

by

R. CHATTOPADHYAY

EWAC Alloys Limited, (A subsidiary of Larsen & Toubro Ltd.), Bombay

A defect is the discontinuity which by nature renders the weldment unable to meet specifications or acceptance standards. Thermal cycle of welding process leads to melting, casting and heat treatment of similar or dissimilar materials which are joined together and thus the defects associated with melting, casting and heat treatment are also found in the welded structure. During the last two decades, development of high yield strength steels e.g. Micro alloyed HSLA, Maraging steel etc. with narrow ductility range and low toughness caused enormous problem for welding fabricator, designer and user. The steels for cryogenic purpose (9% nickel steel) and creep resistance steel need special attention so as to develop necessary sub-zero and creep resistance properites in the respective weld fabricated structure. Significance of the discontinuities with respect to service behaviour assessed with greater sophistication by using fracture mechanics techniques and 'Fitness for Purpose' concept. In this article the nature, origin, effect and prevention of major metallurgical defects encountered in fusion welding processes are discussed.

INTRODUCTION

During the last two decades there has been significant advances in the origin and nature of weld defects and their prevention (Lundin, 1981). Some of the remarkable series of alloys developed during this period :

a) Microalloyed HSLA Steels - For structurals, pressure vessels and pipe lines with exceptionally good combination of high yield strength and toughness (Chattopadhyay et.al.1966), Chattopadhyay (1975), Chattopadhyay (1981). Low transition temperatures of several alloys in this group enabled them to be used in pipeline construction in Arctic region and also for offshore structure.

b) 9% Nickel Steel as high strength material for crygenic purposes, (Chattopadhyay et.al (1970), (Tewari, Chattopadhyay & Bhatnagar (1972). This material has been used extensively for manufacturing tankers carrying natural gas in liquid form.

c) Maraging Steels as an exceptionally high strength material (Chattopadhyay, et.al.1971) for space and nuclear applications

The need for fabrication of these and other newer materials by welding has led us to enquire into more fundamental aspects of defects viz (i) effect of different types of defects e.g. inclusions and its shape, size on fracture characteristics, (Chhattopadhyay 1983), by Modern techniques like SEM/TEM/EDAX.

(ii) Location, shape and size of defects by different NDT techniques including newer accoustic emission or more sophisticated technique like SLAM i.e. Scanning Laser Accoustic Microscopy (Adams 1984). (iii) The significance of defects in relation to service behaviour by fracture mechanics techniques (Nichols 1977).

Nature & Origin of Welding Defects

Thermal cycle of welding process leads to melting, casting and heat treatment of similar or dissimilar materials which are joined together. Therefore all the defects associated with the process of melting, casting and heat treatment processes are found in the welded structure. Defects in fusion welded joints are normally classified into three major groups namely ;

1. Process and procedures related
2. Metallurgical and
3. Design related

Tabel 1 lists these defects in three grous but the defect in one group may be inter-related to that of other group.

Table 1

Classification of weld joint discontinuities

I **Welding Process and ProcedureS Related**

- A) **Geometric**
  - Misalignment
  - Undercut
  - Concavity or convexity
  - Excessive reinforcement
  - Improper reinforcement
  - Overlap
  - Burn-through
  - Backing left on
  - Incomplete penetration
  - Lack of fusion
  - Shrinkage
  - Surface irregularity
- B) **Other**
  - Arc strikes
  - Slag inclusions
  - Tungsten inclusions
  - Oxide films
  - Spatter
  - Arc craters

2. **Metallurgical**

- A) Cracks or fissures
  - Hot
  - Cold or delayed
  - Reheat, stress-relief, or strain-age
  - Lamellar tearing

B) Porosity
   Spherical
   Elongated
   Worm-hole

C) Heat-affected zone, microstructure alteration

D) Weld metal and heat-affected zone segregation

E) Base plate laminations

3. **Design Related**

A) Changes in section and other stress concentrations

B) Weld joint type.

The discontinuities as listed in (1) and partly (3) can be mostly taken care of by making a proper Welding Procedure Specification (WPS) and Procedure Qualification Record (PQR) so that the weldment prepared for construction is capable of providing the required properties for its intended application. This is also the requirement under Section IX of the ASME Boiler and Pressure Vessel Code or the ASME B31 Code for pressure piping.

Metallurgical defects can be overcome by selection of compatible consumables with respect to base material and adopting a welding procedure appropriate for both the parent material and consumable.

Major Metallurgical defects - Origin and Prevention

A) Solidification Crack
B) HAZ Liquation Cracking
C) Lamellar Tearing
D) Hydrogen Induced Cracking
E) Stress Relaxation Cracking
F) Special Problems

A) Solidification Crack

1. Weldment with excessive depth/width ratio is prone to solidification crack.
2. Movement of joint due to heat or distortion may cause solidification cracking.
3. Due to continuous welding constraction on 1st part impose a strain during solidification on the weld on the other side leading to crack. (The Patch Test)
4. Contamination of S or P e.g. in repair welding, articles exposed to S containing atmosphere - covered with sulphide scale.
5. Poor fit-up : Unfavourable weld bead shape, If poor fit-up the weld may have to bridge a wide gap and the depth/width ratio of the bead may be vary small. Contraction of the long bridge of weld metal imposes a large strain on the centre of the weld which itself has a small cross section area.
6. Weld metal used is incorrectly chosen : Tolerance of impurity by the weld metal depends also on the carbon level and alloy balance.
7. Solidification Mode : Crack formation susceptibility in GTA weld deposit of Austenitic, 304, 304N, 321, 316 and 317 is more when the welds solidify as primary austenite than those solidifying as primary ferrite even if the latter is at higher impurity levels (Kujanpaa et.al 1987). The main impurities responsible for solidification cracks are Sulphur and Phosphorous.

B) HAZ Liquation Cracking :

Very high temperature - "burning" i.e. grain boundary liquation due to low melting point sulphides in HAZ and the plastic strain due to welding open up microcracks. Restric sulphur level in parent metal or Mn : S ratio of 20 : 1 - freedom from liquation in 0.2% C - Mn Steel. Carry out bend test of HAZ to indicate the presence of Liquation Crack.

C) Lamellar Tearing :

Low short transverse ductility causes lamellar tearing (Hattangadi and Seth, 1983). Calculated critical sizes of lamellar tears from the following equation for an embedded crack in a weldment (Wessel, 1969)

$$\frac{aCr = K_{1c}\,2\,[\phi^{2} - 0.212\,(\sigma/\sigma ys)^{2}]}{\pi\sigma^{2}}$$

where α Cr = Critical lamellar tear (inch)

K_{lc} = Fracture toughness in ksi.in 1/2

σ = applied stress, ksi σys = Yield stress, ksi

ϕ^2 = Shape factor : for alliptical tear patches $\phi = 1$

Localised stress in the vicinity of tear = 3 σys because of triaxial state of stress.

K_{lc} Values being in the range of 23 to 30 Ksi - in $^{1/2}$

(25.3 to 33 MN m), a band of critical size (2a cr) equal to 0.07 - 0.12" (1.8 to 3 mm) was found, which compared well with the size of lamellar tear patch.

To Avoid :-

i) Improve design of joints
ii) Use forged products
iii) Select Plates with low type II elongated inclusion
iv) Use of low strength weld metal
v) "Buttering" or "grooving and buttering"

soft buttering layer followed by normal weld metal

D) Hydrogen Induced Cracking (Lundin & Menon, 1984) depends on

1) Hydrogen dissolved at high temperature but very low solubility at ambient temperature causes retention of diffusable hydrogen in the structure.

2) Susceptible weld metal or HAZ

Composition and microstructure determine the cold cracking tendency in presence of hydrogen. Hardend martensite is more prone to hydrogen embrittlement than softer microstructure.

3) High level of residual stress accelerates cold cracking tendency.

To Avoid use :

i) Low H electrode/baked
ii) Preheat
iii) PWHT

E) Stress Relaxation Cracking :

(I to and Nakanishi, 1972) SR crack susceptibility of low alloy steels depends on the content of secondary hardening alloying elements and expressed by equation

- PSR= (%Cr) + (%Cu) + 2(%Mo) + 10(%V) + 7(%Nb) + 5(%Ti) - 2

PSR> 0 - cracked ; PSR < 0 - not cracked *

(* The SR susceptibility of high Cr steels (Cr > 1.5%) and extremely low C steels are low inspite of high value of PSR)

SR cracks are intergranular, occurring in HAZ and depend on chemical composition of steel to be welded, residual stress due to welding and occur only in the course of postweld heat treatment when heated above 500°C.

F) Special Problems :

(1) Lamellar Tearing and/or Hydrogen Induced Cracking in HSLA Steels : (Tothwell & Gray 1976, Keeler 1984). Although carbon content of microalloyed steels is restricted to around 0.23%, there has been a number of catastrophic failures in welded microalloyed HSLA structures. After the initial failure of welded heavy structures (e.g. collapsing of a building in Frenchchurch Street in London and bridge in Australia) of HSLA considerable progress has been made on the cleanliness or inclusion control and weldability in HSLA steel.

The increased cleanliness of modern HSLA steels with low S, low inclusion content is a necessary development to prevent lamellar tearing of weld fabricated heavy sections (Chattopadhyay 1983). However, modern low impurity content microalloyed HSLA steels are prone to hydrogen embrittlement and HAZ cold cracking. This is a matter of grave concern for HSLA fabricator. In such situation austenitic electrode is recommended (Dhamdhere, Borate and Chattopadhyay 1983).

(2) Grain Coarsening/Martensite Formation :

Ferritic stainless steels, 400 series, weldment and HAZ are likely to have reduced toughness and ductility due to grain coarsening and martensite formation. To obtain maximum toughness and ductility pre and postweld heat treatment are necessary (Krysiak, 1986).

(3) Weld decay in Stainless Steel : The austenitic and ferritic S.S. are generally supplied in heat treated condition and thus free of carbidee. However , when the steel is welded , the carbide precipitation temperature range (500-850°C) exists at a distance of few millimeters from the weld bead. A zone of carbide precipitates with chromium depleted areas having propensity towards intergranular corrosion will therefore occur parallel to the weld.

At a given temperature, the sensitivity of the zone is determined by the Carbon content and heating time of the steel. An austenitic steel with 0.08% C becomes sensitive after only a few seconds while a steel with 0.02% C will withstanding few hours heating.

Ferritic steels are more sensitive than the austenitic and require considerably lower carbon content to ensure acceptable protection against weld decay. This is because of faster diffusion and lower solubility of C in ferrite compared to austenite and thus greater tendency to form carbides.

To reduce the risk of chormium carbide precipitation and intercrystalline corrosion, the methods adopted are :

a) Reduce Carbon level to normally 0.05% but to 0.02% in case of aggresive media.

b) Stabilise the steel against chromium carbide precipitation by using strong carbide formers like Ti or Nb. When welded, even strong Ti & Nb carbides would dissolve in areas near the weld. Subsequent heating to sensitization temperature during either stress relieving or in additional welding pass give rise to precipitation of chromium carbide, since chromium carbides precipitate faster than titanium carbides reform at temperatures below about 850°C Such chromium carbide precipitates may give rise to a type of intercrystalline corrosion known as 'knife line attack' because it appears in a narrow zone next to the weld. However, this type of corrosion is rare.

c) Cool the material fast through the sensitization temperature range.

N D T Techniques for detection of defects in welding :

Also called Non Destructive Evaluation (N D E) and Non Destructive Inspection (N D I) and commonly used methods are :

1. Visual Inspection with or without Optical aid (VT
2. Liquid Penetrant (PT)
3. Magnetic Particle (MT)
4. Radiography (RT)
5. Ultrasonic (UT)
6. Eddy Current (ET)
7. Accoustic Emmission (AET)

While the techniques (1), (2) and (3) are capable of detecting defects exposed to the surface, the other (4) to (7) are used for identifying surface or interior discontinuities in welded structure.

Two types of flaws :

a) Planar (2D) flaws are cracks and lamellar tears, lack of root penetration.

b) Non-planar flaws (3D defects) cavity type such as porosity, gas holes, worm holes and slag inclusions . also profile defects like undercut root concavity, excess penetration, overlap and misalignment.

Two important aspects of detection by NDI are to find out location and size plus shape of the flaws.

TABLE 2

Average Minimum Flaw Sizes detectable by NDT techniques (J.D.Lavender 1976)

Technique	Type of Flaw	
	Linear (mm)	Round (mm)
Magnetic Particle	4	2.0
Dye Penetrant	4	3.5
Radiography	15	3.0 Clusters
Ultrasonics	10	4.0

A 'defect' is a discontinuity which by nature of effect renders a weldment unable to meet specifications or acceptances standards.

Significance of weld Discontinuities

While a 'discontinuity' may be indicated as lack of homogeneity in the weld structure and hence like 'flaw' is not a 'defect' in the weld. The mere presence of weld discontinuity in a structure may or may not be harmful depending on the material and the stress concentricity. If the stress concentration is not likely to be conducive for the growth of the discontinuity leading to failure then the discontinuity is not a defect and thus acceptable.

Fracture Toughness Concept : Significance w.r.t. Welded Structure : (Nichols, 1977), (Barr & Terry, 1975)

Failure can occur at loads permitted by the relevant design spec. due to presence of discontinuities plus stress introduced by welding. Studies of failures indicate that failure stress in presence of defect decreases with increasing size of defect. Formal relationship between defect size and stress to failure is difficult to derive without making some approximations. One such approximation is that in a large structure made from thick sections of high strength and relatively low toughness material is that failure proceeds general yield. In such cases, the well defined Linear Elastic Fracture Mechanics can be applied, based on the concept that failure will occur when the Local stress intensity factor (K_1) near the tip of defects exceeds a critical value (K_{1c}) and the parameter K_{1c} becoming a measure of the fracture toughness of the material. The stress intensity K and applied stress δ and the defect size parameter 'a' are related as follows :

$$K = F\ (\sigma\sqrt{a})$$

In a simpler form i.e. a thorough crack in a infinite plate, the function F α replaced by $\pi\alpha$. Hence $K_{lc} = \delta c \quad \pi\alpha$ a where δc = Fracture Stress. Using lab value of K_{ic} and knowledge of stresses acting in component this simple equation is rearranged to indicate defect size 'ac' which will just cause failures : viz.

$$\overline{ac} = \frac{1}{\pi}\left(\frac{K_{1_c}}{\sigma}\right)^2$$

A detailed methodology for the protection of welded pressure vessels against non-ductile failure has been defined in Section III of the ASME Boiler & Pressure Vessel Code. This sets out the detailed procedure to be used, including the method for calculating the stress intensity factor K_{1c} reference values for fracture toughness (K_{IR}) of the specified materials and for the size and shape of postulated 'design defect' considered to be very large when compared with the sensitivity of modern NDT techniques.

The above approach (LEFM) is not valid in many of the general engineering applications involving materials of thin section, lower strength and high fracture toughness. In such cases some form of Elasto-plastic or General Yield Fracture Mechanics is required. One approach is that the failure will occur when the local displacement at the crack tip (the crack opening Displacement(COD or δ) exceeds a critical value δc which a material property. Another approach is to avoid uncertainties which arise from concentrating attention on the complex area at the crack tip by determining around the crack the "Path independent integral (J)" which can be defined as the change in potential energy for a unit exten-

TABLE 3

Limits for Inclusions and Porosity

Inclusion length (max.)as welded	Inclusion length (max.) stress relieved	Porosity percentage or Projected area on radiograph	Individual pores diameter
No maximum length max. height or width 3 mm	No maximum length max. height or width 3 mm	5	e/4 or 6mm whichever is lesser

e = thickness

sion of crack length. The concept is that failure occurs when J reaches a critical value J_{1c} which is regarded as the property of material.

"Fitness-for-Purpose" acceptance standards related to fast fracture susceptibility was included in ASME Boiler & Pressure Vessel Code XI, which gives a detailed specification of the methods for judging acceptability of any flaw found by NDT during such inspection. The specification covers first the standardisation of ultrasonic calibration procedures and of reporting levels, the methods for determining a single size parameter for an irregularly shaped defect, and the methods and inputs to be made is the fracture mechanics calculation of susceptibility. The method is based on linear Elastic Fracture Mechanics (LEFM).

The ASME XI is directed at Nuclear reactor pressure vessels, IIW Commission X (Nichols 1977) worked for a proposal of more general workability. A major paper in this group deals with assessment methods of flaws with respect to failure by brittle fracture. The flaws are categorised as a planer (2D) defects such as cracks, lack of prnrtration or of fusion; and non-planer (3D or volume) defects such as solid inclusions, gas pores, shape imperfection including undercuts. Two categories leave different acceptability standards. Those for non-planer defects are given in Table 3.

With planer defects, the acceptability of a flaw is defined in terms of a single size parameter a, and gives detailed rules for relating this parameter to real defects of different types and irregular shapes. The premissible value of 'a' and methods of calculation differ according to the total level of stresses in the flaw region. Primarily, thermal, residual and peak stresses must be added together and if this sum gives a value less than yield, then the stress intensity factor (K) approach of LEFM is used. In such cases where the total stress exceeds the yield stress, the approach is based on General Yield Fracture Mechnics and the measurement of assessment of fracture toughness is by critical crack opening Displacement (δc).

In brief the flaw is regarded as acceptable if its equivalent defect size parameter 'a' is less than a tolerable value am. where

$a = C(K_{1c} / \sigma y)^2$ where σ Total < σy

$a = C(\delta / ey)$ " σ Total > σy

Where C = Constant, ey = Yield strain

Wide plate tests have been designed to assess the significance of various defect types (e.g. surface & through thickness) located in the different regions of a welded joint e.g. weld metal and HAZ. These tests can give an accurate picture of the combined influence on critical crack size of applied stress and residual stress and can also assess the influences of stress concentration features by placing defects close to welded attachments. The results of such tests (Baker, Barr, Gulvin, Terry, 1973) (Daves, 1974) have confirmed that the defect tolerance calculations produce conservative predictions of a with reference to ac.

In actual service condition, other failure modes should also be considered such as fatigue and stress corrosion, which can cause growth of small defects towards critical crack size.

Estimation of stress level in welded structure :

(Barr & Terry, 1975), (Harrison, 1980). Residual stresses develop during welding due to uneven beating and cooling, phase transformation and also due to non-elastic strain may lead to following fundamental dimensional changes (Masubuchi, 1981) :

a) Transvers shrinkage perpendicular to the weld line

b) Longitudinal shrinkage parallel to the weld line

c) Angular distortion around the weld line.

In order to assess fracture toughness of material we need to measure or estimate stresses in the particular part of the structure where defect exists. The stress concentration can be measured by various methods as shown in Table 4 :

Residual stresses due to welding need to be taken into account while calculating the tolerable defect size. The maximum residual stress which can exist corresponds to the yield strength of the material. The effect of residual stress can be pronounced when service stresses are low reducing effectiveness of the term δa x SCF in $\delta = \delta a \times SCF + \delta_R$;

(δ=stress acting on the defect, δa = applied stress, SCF - Stress Concentration Factor, δR = residual stress) in total stress calculation. A specific case of 100 mm thick MS fabrication with a maximum operating pressure of 45 - 75 N/mm² can be cited. Defects

TABLE 5

Defect Size Calculation in Weld

Condition	(N/mm^2)	SCF	(N/mm^2)	a
A) M.S.WELD (Ref.3)				
1. As welded	75.0	1	Y	6.3
2. As welded	"	3	Y	4.5
3. Stress Relieved	"	3	0.25 Y	13.5
4. Stress Relieved	"	3	Nil	29.0
B) 9% Ni Steel welded with matching electrode (Ref. 17)				
1. At 77°K	294 (σd)	3*	365	5.12
2. Stress Relieved (77°K)	294 (σd)	3*	0325R	8.40

(* SCF = 3 at 77°K, assumed value)

were found in the weld during routine inspection caused by lack of fusion. The toughness of the weld in which the defects were located was 0.074 and 0.091 mm COD as determined from laboratory toughness tests in the as-welded and stress relieved condition respectively. A comparison of defect sizes calculated for the as welded and stress relieved condition are shown in the following Table 5 :

Comparing the tolerable defect sizes for condition A1 & A2 indicate the small influence of the factor assumed for stress concentration where the operating stresses are low. In addition, the calculation illustrates the marked influnce of the value selected to represent residual stresses. There is some controversey about the effect of thermal stress relief in reducing or eleminating residual stress. In the example given there is a significant difference in a value depending on the assumed value for residual stress (condition A3 & A4).

Based on the work done by Koshiga (1984) using fracture mechanics technique in weldment of 23 mm thick 9% nickel steel plate joined by matching consumable where Kc = 5000 N $mm^{-3/2}$ at 77°K (-196°C) and design stress δa = 294 $/mm^2$ and residual stress δR = 365 N/mm^2 and 0.2% P.S. = 728 N/mm^2 the calculated 'a' values are 5.12 in as-welded and 8.40 in stress relieved condition.

In case of fully austenitic welded joints although much valuable information with regard to hot

TABLE 4 SUMMARY OF METHODS FOR STRAIN & RESTRAINT MEASUREMENT

Technique	**Approx. Temp. Limit (°C)**	**Advantage**	**Disadvantages**
1. Electric Resistance	400	a. Cheap and simple b. Well known technique	Cannot use near weld due temp limitation
2. Opto-Mechanical Guages	300-1000	High temp. capability	Delicate equipment, may be difficult to use
3. Brittle Lacquer	370	a Cheap & simple b Strain picture over large area	a Temp. limited for use near weld b Cannot measure transient strains c No measurement possibe during welding
4. X-ray diffraction	R.T.	a No cantact with specimen b Almost a point measurement	a Equipment bulky and expensive b Cannot measure transient strains c No measurement is made on immediate surface only
5. Moire Fringes	Melting point of grid material	a Strain picture over a large area b High limit to temp c Can measure elastic-plastic strains.	a Incapable of following transient strains b Time consuming c Measurement during welding d Totally destructive for internal strain measurement
6. Holography & speckle pattern Interferometry	R.T.	a No specimen preparation b Accurate c Can measure elastic-plastic strains d can monitor transient strains	a Extreamly sensitive to convection current set up by a heated body b Small size specimen only c Lab methood only
7. Capacitance strain guages	600 - 800	a Accurate, height temp. guage b Small c Easy to use	a Localised strain only b Limited size of guage length available
8. Hickson Replica	Melting point of materials on which lines are scribed	a Can measure elastic-plastic strains b Short guage length c Grid not destroyed by welding unless melted	a cannot measure transient strains b Measurement not possible during welding

cracking and the precipitation are available the data with respect to tolerable magnitude of existing cracks constituting an actual risk to the welded vessel are not available (Robensteiner and Tosch, 1985).

For SG Ni-Resist type Cast Iron of 25 mm thick, K-butt welded with ferro-nickel electrode, and K max = 1660 $N/mm^{-2/3}$, operational stress = (Proof stress (residual stress) + Design stress (20% UTS = 355 N/mm^2, calculated permissible total crack length is 13 mm (Stephension, 1976).

Fatigue vs Fracture Mechanics in Design :

Actual service life of pressure vessels was found to be less by a factor of 8 to 4 than the designed life based on fatigue data. Subsequent research showed that in pressure vessels, however carefully manufactured, always contained a population of small discontinuities and the fatigue life of the vessel is controlled by the growth of these discontinuities rather than the crack initiation and growth as is measured in typical S-N curves. Thus the emphasis has been shifted to a fracture mechanic characterisation of crack growth i.e. growth rate (da/dn in inch/cycle) is plotted against ΔK the stress intensity factor at the tip of the growing crack. (Pense, 1980) The increasing use of fracture mechanism is not only to characterize the fracture toughness of materials but also to characterise crack growth has been one of the most remarkable changes in the characterisation of materials that have taken place during the last twenty years.

Fracture mechanics has been used to analyse and get acceptable defect level in fabrication of Nuclear Reactor Pressure Vessel (Section XI of ASME Boiler & Pressure Vessel Code), Super tankers (Harrison 1980), modern military aircrafts (Jones, 1982), Trans Alaska Oil pipelines (Southwest Research Institute Rep.1976) and Alaskan Gas Highway Project (Alberta Corp. Report 1981).

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