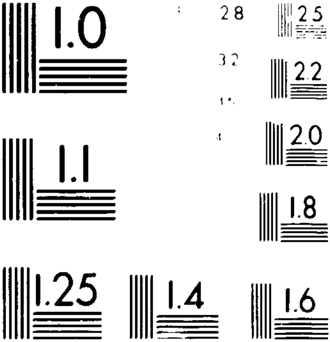

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AN OVERVIEW OF ENGINEERING MATERIALS FOR WELDED STRUCTURES AND METALLURGICAL PROBLEMS IN FABRICATION INDUSTRY - PART II*

by

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1.0 INTRODUCTION

Besides metallurgical aspects, when one considers the strength of a structure that is welded, several additional factors are involved, the most important of which are occurrence of weld defects, residual stress and distortion.

In the conventional analysis of the tensile strength, fatigue strength, the buckling strength etc, of a material, idealistic conditions of material and structure are assumed. However, a realistic welded structure is inhomogeneous, comprising of the weld, the HAZ and the unaffected parent material zone, contains various types of defects, carries initial residual stress and has initial distortion.

In this paper, the effect of these imperfections on the service performance and reliability of any welded structure, alongwith the appropriate procedures that are to be followed to overcome these problems during fabrication to achieve a sound weld are discussed.

2.0 WELD DEFECTS

Welds often contain various types of defects. Some of them are -

1) Porosity
2) Slag inclusions

3) Incomplete fusion
4) Inadequate joint penetration
5) Undercut
6) Cracks
7) Arc strikes
8) Defective weld profiles

Porosity refers to gas packets or voids free of any solid material, frequently found in welds. It is caused when gas is released as a weld metal cool and its solubility is reduced and from gases formed by chemical reactions in the weld. Porosity may be scattered uniformly throughout the weld, isolated in small areas, or concentrated at the root (Refer Fig.1). It is usually caused by excessive welding temperatures or incorrect manipulation.

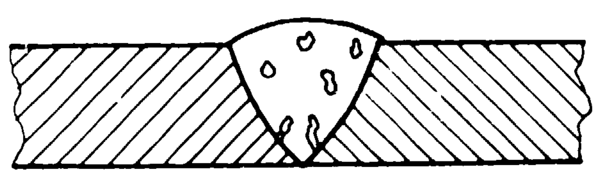


FIG.1 POROSITY

Slag inclusions occur due to entrapment of oxides and other non-metallic solids in the weld or between the weld and base metal. They generally come from flux covering or fluxes employed during welding. Failure to remove slag in a multilayer welding may also result in slag inclusions (Refer Fig.2).

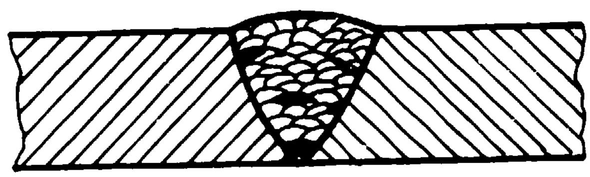


FIG.2 SLAG INCLUSIONS

Incomplete fusion or lack of fusion as it is otherwise called, is the failure to fuse together adjacent layers of weld metal or adjacent weld metal and base metal. It may be caused by failure to raise the temperature of the metal or previously deposited metal to the melting point, or failure to remove mill scale, slag, oxides or other foreign material present on the surface (Refer Fig.3).

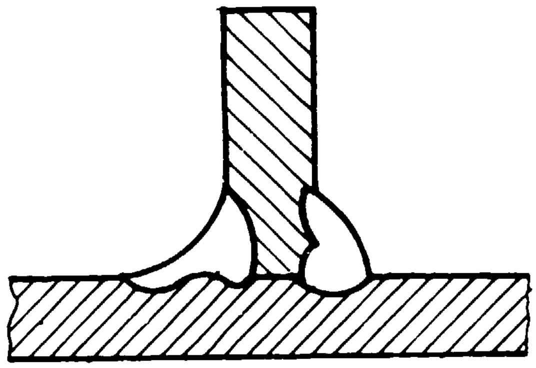


FIG.3 INCOMPLETE FUSION

Inadequate joint penetration is a condition in a joint where the joint penetration is less than the specified. Hence, partial joint penetration may or may not be a defect depending on what is specified for a particular joint. Undercut is a groove melted into the base metal adjacent to the toe of a weld and left unfilled by the weld metal. It also describes the melting away the side wall of a groove at the edge of a layer of bead, thus forming a sharp recess in the side wall in the area to which the next layer or bead must fuse (Refer Fig.4)

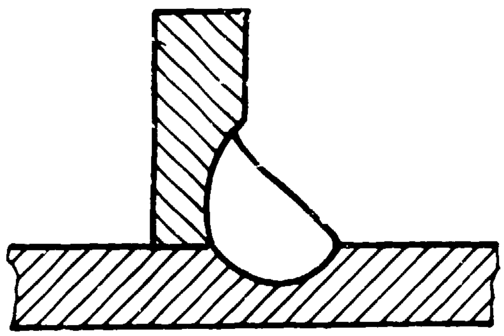


FIG.4 UNDERCUT

Cracks result from ruptures of metals under stress. Although sometimes large, they are often very narrow separations in weld or base metal. Cracks are one of the most harmful defects. Apart from like hot, cold and solidification cracks, crater cracks can also occur due to inadequate manipulation during welding (Refer Fig.5).

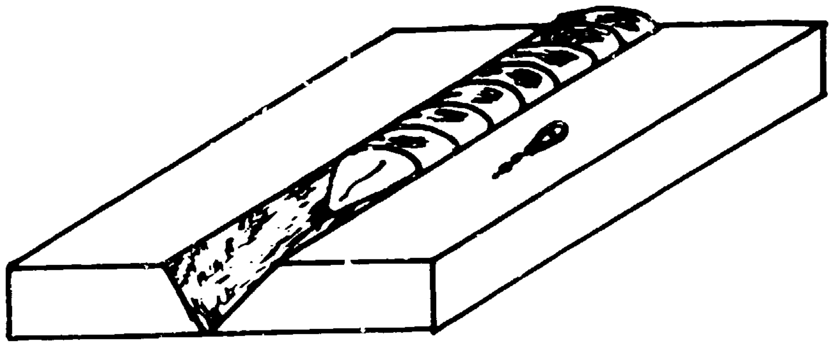
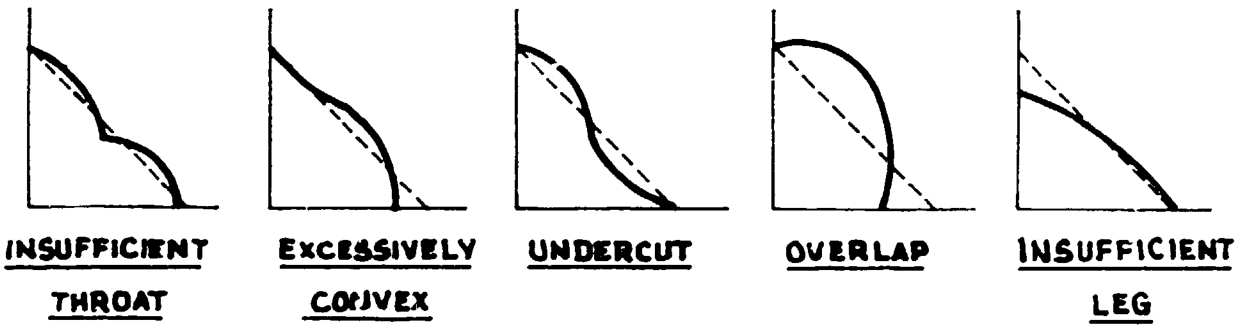


FIG-5 CRATER CRACKS AND ARC STRIKES

Although arc strikes are not normally considered defects, fractures (brittle and fatigue) frequently initiate from arc strikes. They are formed during unintentional melting of areas outside the intended weld deposit area (Refer Fig.5).

The profile irregularities describe the conditions when the profile of the bead or welds are not regular or uniform with rough bead appearances. For example the bead may be either overlap or protrude beyond the bond at toe of weld or may not cover it (Refer Fig.6).

FIG.6 DEFECTIVE WELD PROFILES



It may also be excessively convex with heavy reinforcements or excessively concave. These defects are mostly caused due to improper manipulations.

3.0 CONSEQUENCES OF WELD DEFECTS

As these above said defects occur mostly in regions near the weld where high residual stresses exist the extent of its influence depends on the severity of the defect. However, there are two reasons how the weld defects reduce the strength of welded joints. First the presence of defects reduces the sectional areas. Second stress becomes concentrated around these defects or discontinuities. The content to which weld defects affect the structural strength depends on -

1) Nature and extent of defects;
2) Properties of the material;
3) Types of loading

Defects such as porosity and slag inclusions cause less severe stress concentrations and so are less harmful. However, these defects affect the transverse tensile strength of welded joints. An appreciable reduction in the static strength occurs when the defective area amounts for 5% or more of the sectional area. A 10% loss of sectional area causes a 10% reduction in strength, both in steel and aluminium welds. The effect is severe when they are present near the surface.

From defects such as undercuts, arc strikes and cracks a fracture may get initiated resulting in a

catastropic failure if the material were brittle or becomes brittle due to excessively low ambient or severe temperature conditions. As severe stress concentration and triaxial stresses are produced near areas containing these defects they are the vulnerable locations for the fracture to get initiated. This is more so in high strength steels. Hence the severity of these defects is more critical in such high strength steels.
Welds containing porosity, slag inclusions, lack of fusion also tend to reduce the fatigue strength of materials to about 40% and the cycles for failure to one tenth compared with that of sound weld.
As fatigue fractures usually initiate from surface defects present in surface or near the surface are more damaging than that are present in mid thicknessess. In particular the weld reinforcement and the weld profile influences the fatigue strength to a larger extent than other factors. It is found that the fatigue strength decreases by 50 to 60% if excessive reinforcements are present. The failure is more inevitable if the weld profiles are irregular and rough in appearance.

4.0 FABRICATION TECHNIQUES AND PROCEDURES TO MINIMISE WELD DEFECTS

Most of these defects discussed above is attributable to workmanship and practice of improper procedures to a larger extent and negligence of precautions to a smaller extent. Apart from following proper preheating, postheating procedures depending upon the materials, good workmanship to eliminate these defects through simple techniques and adherence of the precautions must be practiced. Some of the precautions to obtain welds free from these defects are -

1) To take adequate care on cleaning the joint, and the filler wire, if necessary;
2) To maintain proper fit up conditions;
3) Use of optimum welding parameters;
4) Use of appropriate preheat and postheat levels;
5) Use of proper welding techniques like crater filling, arc striking, weaving, etc;
6) To take adequate care in the finish of the weld surface i.e., dressing of welds;
7) To use materials with higher fracture toughness.

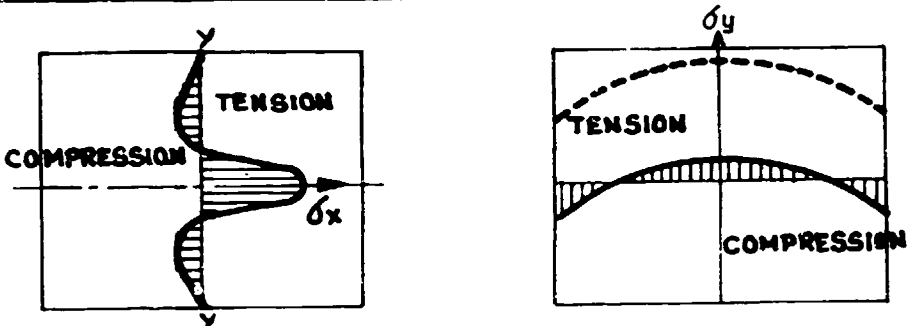
5.0 RESIDUAL STRESSES

Residual stresses are those stresses that would exist in a body if all external loads were removed. These are caused when a body is subjected to a non-uniform temperature change like in welding in which case are also called thermal stresses.

During welding a weldment undergoes complex temperature changes. Due to plastic deformations in areas that attain high temperatures non-elastic strains are produced in regions near the weld whereas elastic strains are produced in areas away from weld. Due to the development of these incompatible strains in localised areas residual stresses remain even after welding is complete.

In general tensile residual stresses are produced in the weld and regions near it whereas compressive residual stress occur in regions away from it. Fig.7a, 7b show the distribution of the longitudinal

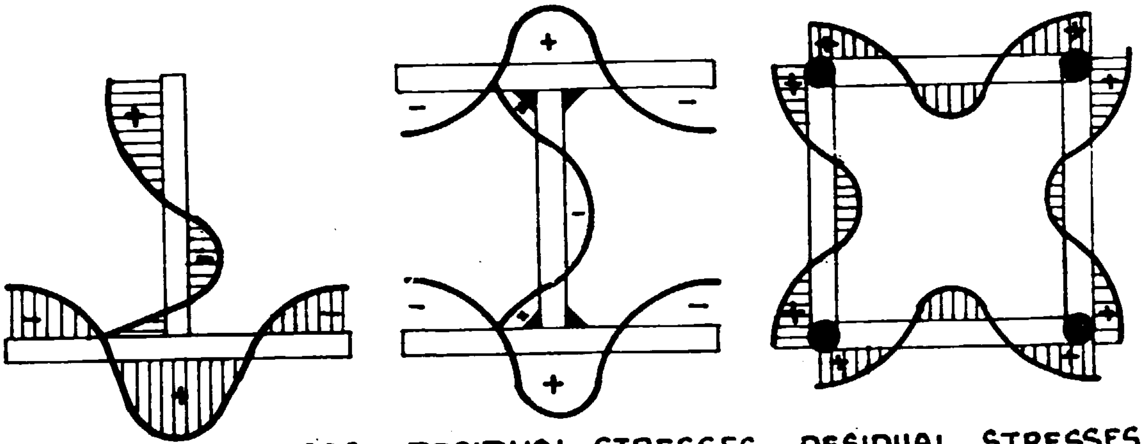
FIG.7 TYP. DISTRIBUTION OF R.S IN A BUTT WELD



7a - σ_x ALONG YY.   7b-σ_y ALONG XX.

residual stress and the transverse residual stress respectively in welded plates. Tensile residual stresses of the order of yield stress level are produced in the longitudinal direction whereas stresses of the order of 0,35 times the yield are produced (when the plates are free) in the transverse direction. Fig.8 shows the residual stress distributions produced in welded T-shape, H-shape and box-shaped structures.

FIG.8 RESIDUAL STRESSES IN BUILT UP STRUCTURES



RESIDUAL STRESSES IN T- SHAPE

RESIDUAL STRESSES IN H- SHAPE

RESIDUAL STRESSES IN BOX SHAPE

6.0 FACTORS THAT INFLUENCE RESIDUAL STRESS

As residual stresses are basically produced due to incompatible thermal strain, heat input is the primary factor that influences residual stress. Apart from this the material thickness and geomerty, the material chemistry and metallurgical transformations that occur during welding of the material and welding procedures like preheating, welding sequence etc., also influence the magnitude and distribution of residual stress.

The width of the tensile residual stress zone increases as the linear net heat input increases though the effect is not linear. Regardless of welding conditions maximum residual stress reaches the yield stress at room temperature.

As far as materials are concerned it is found that the distribution pattern changes with the type of material. Even compressive stresses have been noticed in the weld region in certain high alloy steels such as maraging steels. These changes are due to stresses produced due to phase transformations that occur at fairly low temperature in these steels.

7.0 EFFECTS OF RESIDUAL STRESS

Residual stresses in weldments have two major effects. First, they produce distortion and second they may act as the cause for the premature failure in weldments. The first effect being a major one it is treated separately. Secondly premature failure of weldments may occur due to any of the following viz., brittle fracture, fatigue fracture stress corrosion and reduction of buckling streength in the case of columns.

1) Brittle fracture is a fracture that occurs without vvery little or no plastic deformation or ductile flow at fairly low applied stress levels and at low temperatures originating mostly around notches. If notches or flows are present in areas where tensile residual stresses are present then the fracture may occur either at lower levels of stresses or even at normal temperature.

   In order to eliminate this problem stress relieving treatment is a solution. Residual stress affects the fatigue fracture strength of a welded structure to a considerable extent.

Fatigue fracture is a fracture that occurs that takes place after a certain number of cycles during the application of a repeated loading. In the presence of tensile residual stresses both the number of cycles required for the crack initiation and the fatigue fracture strength occurs at lower values causing a reduction in fatigue strength. However, it is also found that compressive residual stresses are beneficial as far as fatigue strength is concerned.

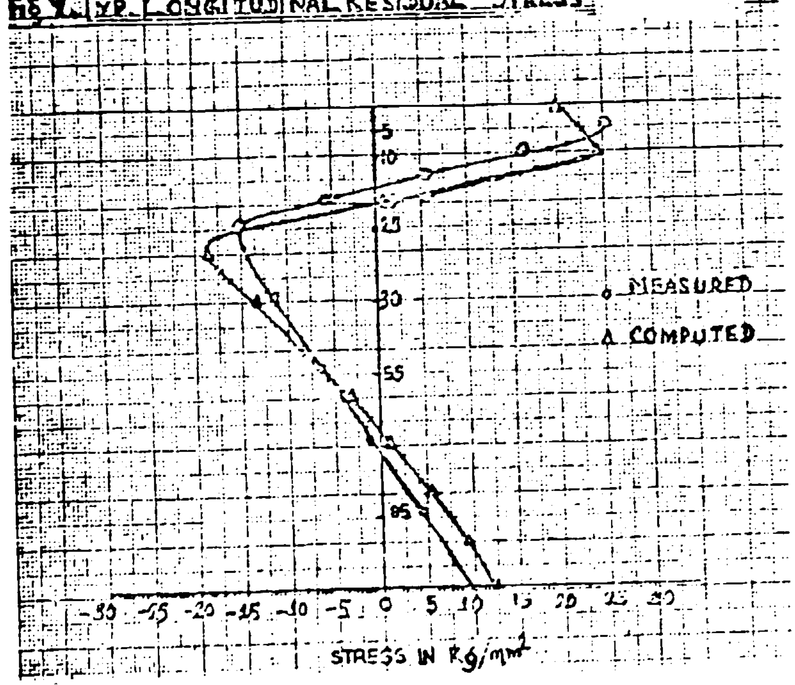
Failure due to instability or buckling occur in thin metal structures composed of stiffener plates when they are subject-d to compressive axial loads. Residual compressive stresses decrease the buckling strength of a metal structure and in addition initial distortions caused by residual stresses also decrease the buckling strength. In general the presence of compressive residual stresses has the following effects -

1) It adversely affects the strength of straight structures;
2) It affects buckling strength of stiffened plate structures

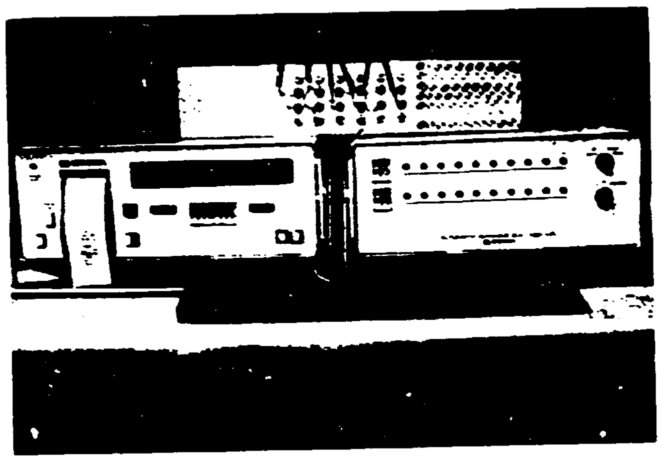
Apart from these the presence of residual stresses also affects the dimensional stability of structures. Stress corrosion cracking is another type of cracking that occurs in weldments even without external loading, when the material is embrittled by exposure to certain environments and when residual stresses are present. This cracking is more prone to occur in areas where tensile residual stresses are present.

7.1 Hence as described above, the presence of Residual Stress is not desirable. But unless a proper understanding of the kinetics of the development of stress is known, its after effects cannot be eliminated fully. In tune with this a successful attempt has been made to analyse the development of these stress through an analytical model using the computer which was also verified experimentally. Fig.9 shows a typical comparison of results obtained between the experiment and computed values for edge welded steel plates conforming to ASTM SA515 Gr.70.

FIG 9. TYP. LONGITUDINAL RESIDUAL STRESS



The digital strain indicator which was used for the measurement of residual stress is also shown through Photograph-1.



All the above types of failures can be prevented by stress relieving treatments either by thermal or mechanical means.

8.0 STRESS RELIEF TREATMENT

Removal of stresses can be done by either thermal treatment or by vibration treatment.

8.1 Thermal Stress Relief Treatment is defined as the uniform heating of a structure to a suitable temperature, holding at this temperature for a predetermined period of time, followed by uniform slow cooling.

TABLE-1

TYPICAL THERMAL TREATMENT FOR WELDMENTS

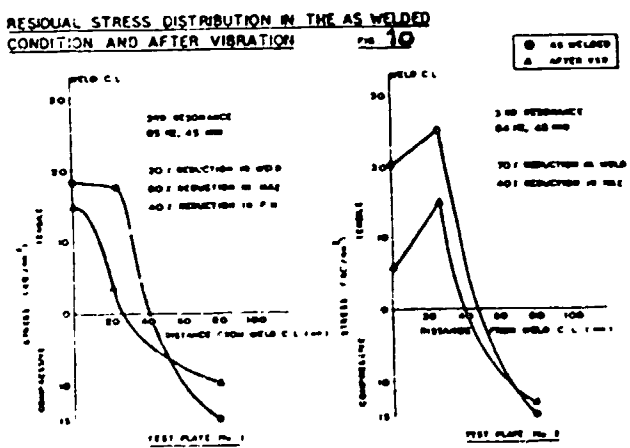
Material	Soaking Temperature °C
Carbon Steel	595 - 680
Carbon - ½% Mo steel	595 - 720
½% Cr - ½% Mo steel	595 - 720
1% Cr - ½% Mo steel	620 - 730
1¼% Cr - ½% Mo steel	705 - 760
2% Cr - ½% Mo steel	705 - 760
2¼% Cr - 1% Mo steel	705 - 760
5% Cr - ½% Mo (Type 502) stee	705 - 770
7% Cr - ½% Mo steel	705 - 760
9% Cr - 1% Mo steel	705 - 760
12% Cr (Type 410) steel	760 - 815
16% Cr (Type 430) steel	760 - 815
1¼% Mn - ½% Mo	605 - 680
Low alloy Cr-Ni-Mo steels	595 - 680
2 to 5% Ni steels	595 - 650
9% Ni steels	550 - 585
Quench & tempered steels	540 - 550

This is a very effective way of reducing the stresses and if properly done under controlled conditions can effectively reduce 80% of the stresses present. The temperature reached during the treatment has a greater effect in relieving stresses than the length of time the specimen is held at that temperature. Though this treatment is very effective precautions must be taken to select a temperature that will develop the desirable properties in steel while at the same time providing maximum stress relief. Table-1 indicates the recommended temperatures for a few steels.

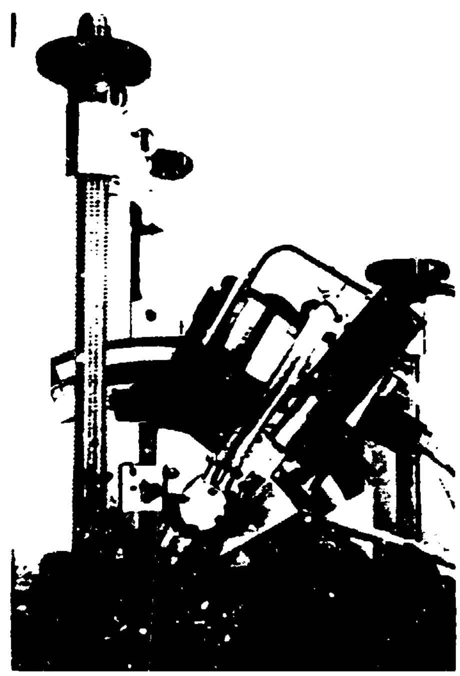
8.2 Vibration Stress Relief Treatment:

Mechanical energy of low and high frequency vibrations are used to relieve residual stresses in weldments. The welded part is vibrated at one of its natural frequencies by clamping the part on to a mechanical vibrator. Though it is not as effective as thermal stress relief treatment it minimises the peak stresses present in the structure. Studies conducted at our Institute showed that it was effective in minimising the peak stresses on an average of upto 50%. Fig.10 shows the effect of VSR treatment on a typical butt welded plate obtained during the trials conducted at our Institute.

RESIDUAL STRESS DISTRIBUTION IN THE AS WELDED CONDITION AND AFTER VIBRATION



For the measurement of stresses the X-ray stress analyser was used (as shown in Photo-2).



9.0 DISTORTION

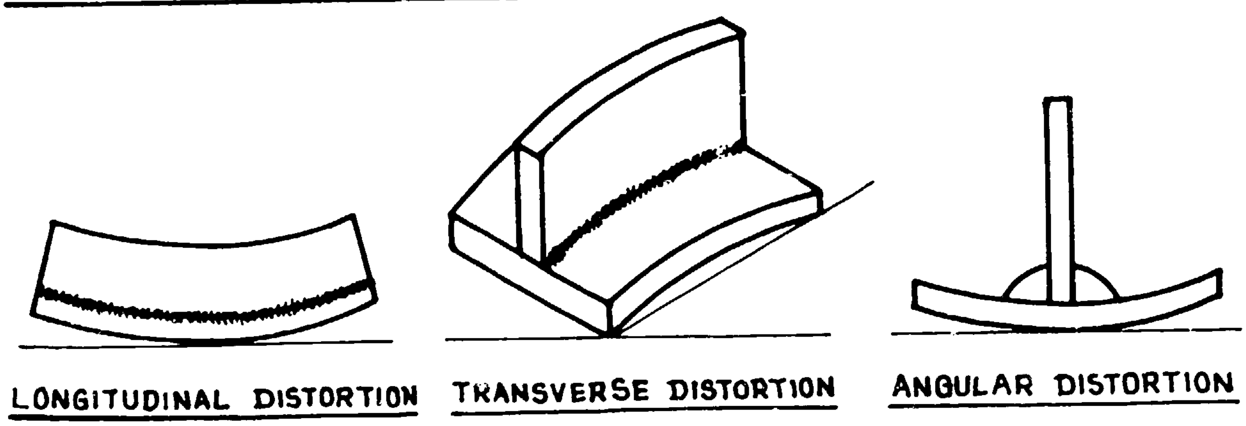
It is caused when the heated weld region contracts non-uniformly, causing shrinkage in one part of the weld to exert eccentric forces on the weld cross-sections. The weldment strains elastically in response to these stresses and this non-uniform strain is seen as macrospic distortion.

Distortion produced in fabricated structures is caused by three fundamental dimensional changes that occur during welding -

1) Transverse shrinkage that occurs perpendicular to weld line;
2) Longitudinal shrinkage that occurs along no weld line; and
3) An angular change that causes rotation around weld line.

All the three changes are shown in Fig.11.

FIG. 11 TYPES OF DISTORTION



In an actual structure all the three dimensional changes occur giving rise to all the three types of distortions viz., transverse, longitudinal and angular. In this structures another type of distortion called buckling distortion also occurs.

10 .0 FACTORS THAT INFLUENCE DISTORTION

The factors that influence distortion can be classified under three parameters -

1) Structural parameter
2) Material parameter
3) Fabrication parameter

In the structural parameters category, joint type, plate thickness and geometry are the factors that are of importance. Distortion increases when groove angle is increased in groove welds. It reduces as thickness increases for a given level of heat input.

In the material parameters category the thermal expansion coefficient, the thermal conductivity and the yield stress of the weld metal are the factors which are of importance. Distortion is found to increase as thermal expansion coefficient increases and thermal conductivity decreases.

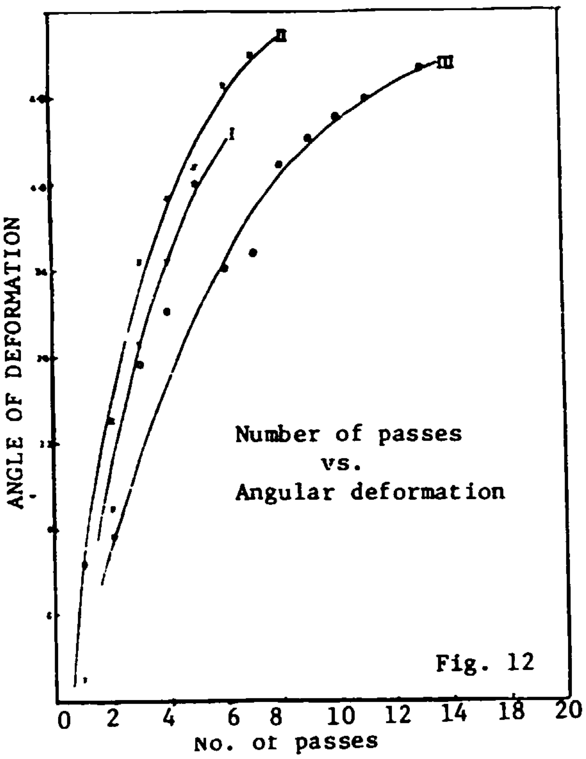


Fig. 12

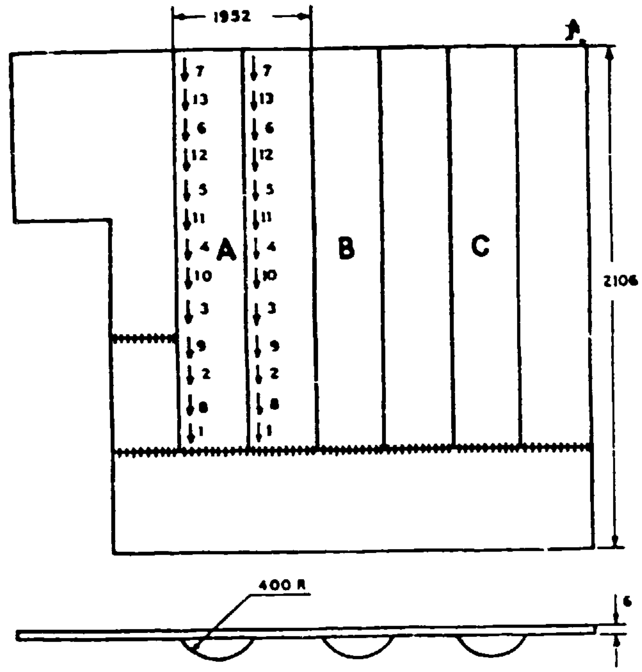


FIG: 13 Back Step Sequence Technique as Applied to the Tank Wall

It is also found that residual stress is lower for higher strength steels.

In fabrication parameters, the process, the heat input, the rootgap, the number of passes used, preheating, postheating, assembly procedure, sequencing and gouging are some of the factors that are to be considered.

In general distortion rises as the net heat input increases. While employing manual metal arc welding use of larger dia electrodes during the initial runs is beneficial. Compared to manual metal arc welding, CO_2 welding produces lesser distortion. Root gap is another important factor which influences distortion in a directly proportional manner. As far as distortion is concerned welds made with fewer number of passes are better. Fig.12 shows the relationship between distortion and number of passes in the case of multipass welds in butt joints using submerged arc welding process. Though preheating and postheating are seldom done to prevent distortion, these treatments minimise distortion. Weld sequencing is another factor to effectively control distortion especially in thin sheet structures. An extensive experimental study conducted at our Institute on the effect of sequencing on distortion during the fabrication of Transformer Tank Casing revealed that sequencing is very effective to minimise distortion in thin plate structures (Refer Fig.13). Though gouging has little effect on distortion can affect distortion when not done with proper precautions.

11.0 EFFECTS OF DISTORTION

Presence of initial distortion has the following effects -

1) It may affect the major functioning of the component itself;
2) It reduces the axial buckling strength of columns;
3) It makes final assembly more difficult for matching;
4) It also reduces the load carrying capacity of the structure;

5) It affects the dimensional stability of a welded structure.

12.0 DESIGN AND PROCEDURES FOR REDUCING THE RESIDUAL STRESS AND DISTORTION

12.1 Reduction of Residual Stress:

Although the extent of the effects of residual stresses on the service performance of welded structures varies significantly, it is preferable to minimise the residual stresses. In order to do that the following precautions should be taken.

1) Since residual stress and distortions are caused by thermal strains, a reduction in the amount of weld usually results in reduction of stresses and distortion. It can be achieved by use of alternative groove preparations like unsymmetrical double V, U preparations.

2) It is disusable to use bevel angles and root openings in the smallest size possible that will not affect accessibility;

3) Attempt must be made to minimise the weld sizes that satisfies the strength considerations

4) Use of weld sequencing techniques may be employed to minimise stresses.

12.2 Minimising Distortion:

Though the above mentioned aspects may still minimise distortion, it cannot be solely controlled by good design and well chosen details alone. There are lot of practical ways by which one can minimise distortion during fabrication which are described below:-

12.3 **Assembly Procedure:**

1) Distortion can be controlled by presetting i.e., the members to be welded are preset to compensate for the distortion that is likely to arise which is estimated. This method is difficult to apply in weldments having larger thicknesses.

2) By assembling the job in such a way that it is welded under highly restrained conditions. These restraints may be applied either in the form of clamps, fixtures or by simple tack welds. While this method minimises distortion it can result in high residual stress that can cause cracking. To overcome that use of proper weld sequencing or preheating is usually resorted to. In certain cases stress relieving treatment may also be done to minimise both residual stresses and distortion.

3) In certain cases involving thicker weldments distortion may be taken care by providing extra material thicknesses as allowance for machining.

4) In certain cases dealing with thinner sections distortion can be controlled by the application of heating and stretching together.

5) Apart from these several other techniques can be employed like for instance using sequences

for welding and by using special narrow gap welding techniques.

13.0 CONCLUSION

In summary welded structures are by no means free of problems although are economical and versatile. Hence in order to design and fabricate a sound welded structure, it is essential to have the adequate design, proper selection of materials, adequate equipment and proper welding procedures, good workmanship and strict quality control.

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