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Why do welds crack?



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Neville Gregory's career as a metallurgist spanned 40 years up to his retirement in 1990. After working at The English Electric Company, Rugby, Murex Welding Processes and Enfield Rolling Mills he joined the London office of BWRA as a Welding Technologist. For six years he carried out liaison visits to members and dealt with technical enquiries.

This work continued when he joined the Research Station at Abington and was combined with contract research on various welding processes and materials including zinc coated steels, low alloy steels, reinforcing bars, and armour plate. Since 1975 Neville Gregory headed a Welding Advisory Service in the Arc Welding Department assisted by a team of Welding Engineers.

Cracking of arc welded joints during fabrication often requires expensive rectification but it can be avoided by an appreciation of its causes, as **Neville Gregory** explains.

Fabrication cracks in welded joints in either the weld metal or the heat affected zone of the parent plate can occur during welding, or occasionally up to several days or longer after welding has been completed. This type of cracking is associated directly with the welding procedure and is quite distinct from service cracks such as fatigue or brittle fracture which may occur at any time during the life of a structure if conditions are appropriate.

Cracks and other planar defects such as lamellar tears and lack of fusion are not permitted by any codes of practice, however small the cracks may be. This requirement may appear to be unnecessarily stringent but a welding procedure that produces cracks, whatever their size, is totally unreliable and may lead to expensive repairs.

Sometimes when small cracks are discovered at a late stage in fabrication of a large structure repair of the defects by gouging out and rewelding with control of preheating and interpass temperatures may be difficult. It is possible to calculate allowable crack sizes using a fitness-for-purpose approach but this is only feasible when the sizes of the cracks in the components can be determined by non-destructive examination and the maximum service stresses are known.

A fitness-for-purpose analysis involves calculation of the maximum growth of the cracks under fatigue loading, and a knowledge of the required toughness levels of weld metal, heat affected zone and parent plate to avoid brittle fracture during the peak loadings envisaged for the structure.

Such an exercise, if possible, is expensive even if it does show that repair of defects is unnecessary.

Rectification of defects by gouging out and rewelding costs 10-20 times as much as production of sound welds and the effect on profit margins is obvious.

Most jobs are costed on the assumption that the weld quality required will be achieved. This is sensible provided that an allowance has been made for realistic welding procedure qualification testing and that all the welding operations are carefully supervised and controlled.

Procedures must be adopted to avoid cracking and this objective can be accomplished with the aid of a knowledge of the principal causes of cracking.

The two commonest forms of cracking are weld metal solidification cracking and hydrogen cracking, either of the weld metal or the heat affected zone of the parent metal.

Three factors control the cracking tendency of welded joints - geometrical, metallurgical, and the level of stress or restraint. These factors interact but it is convenient to consider them separately.

Solidification cracking

Solidification cracking is a common form of weld metal cracking sometimes referred to as hot cracking or centreline cracking. It is generally produced during the final stages of solidification.

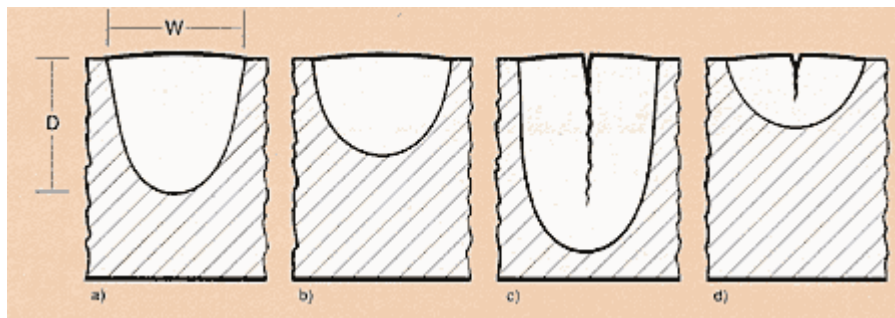
Geometrical factors

These depend to a large extent on the welding procedure, which should be under the control of suitably qualified personnel *e.g.* a welding engineer.

The shape of a weld in terms of its width to depth ratio has a marked influence on its solidification cracking tendency, which can be minimised by ensuring that this ratio is between 1 and 1.4. (*Fig. 1*)

Fig. 1. Effect of weld shape on cracking tendency:

- a) $W:D = 1$, sound weld
- b) $W:D = 1.4$, sound weld
- c) $W:D = 0.7$, weld tends to crack
- d) $W:D = 2.0$, weld tends to crack



Butt welds

Large root gaps either in backed or unbacked joints can cause formation of concave root runs having large width to depth ratios (*Fig. 2*). This can cause solidification cracking similar to crater cracking that occurs at the end of a weld if the crater is not filled. Centreline cracking may also occur in multipass welds if the weld beads have a concave profile (*Fig. 3*).

Fig. 2. Effect of shape of root run:

- a) Incorrect, top concave
- b) Correct, flat or slightly convex

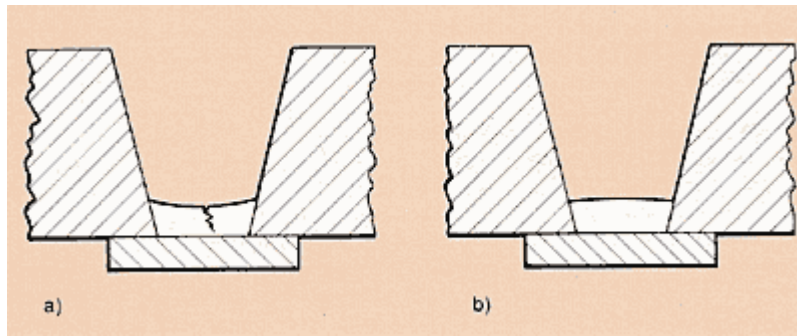
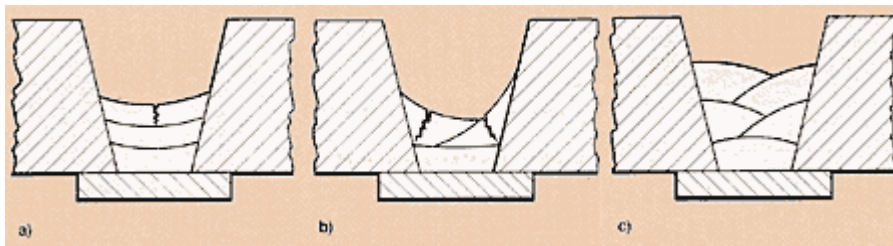
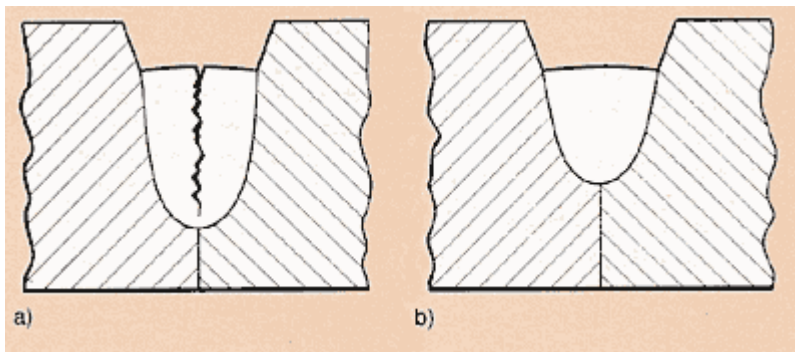


Fig. 3. Effect of weld shape in multipass welds:
 a & b) Concave with tendency to crack
 c) Slightly convex weld beads



Deep penetration welding procedures using submerged-arc, spray transfer MIG, or manual metal arc welding with cellulosic electrodes can provide useful economies, but care must be taken that they do not produce deep narrow welds with high cracking tendencies (*Fig. 4*).

Fig. 4. Cracking tendency of deep penetration weld:
 a) Incorrect shape
 b) Correct shape



Fillet welds

The same principles apply to fillet welds, which should have flat or slightly convex profiles with width to depth ratios between 1 and 1.4.

Large gaps between component parts should be avoided because they encourage deposition of wide weld beads having small throat thicknesses (*Fig. 5*).

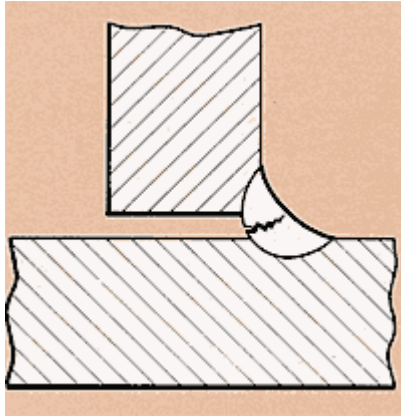


Fig. 5. Bridging large gap gives concave weld

Single fillet welds made by deep penetration processes can result in savings in both welding times and quantities of consumables used but if the depth of fusion is sufficiently greater than the width of the weld solidification cracking may occur (*Fig. 6*). If the depth to width ratio of the weld is excessive the cracks may not reach the surface and cannot be detected by visual inspection.

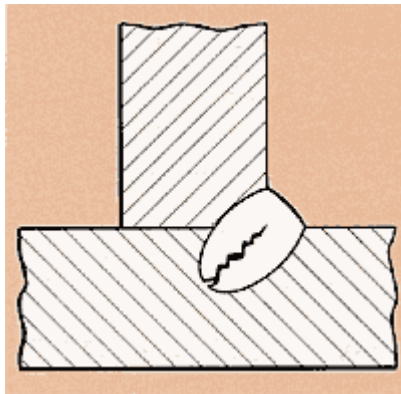


Fig. 6. Cracking of deep penetration fillet weld

The quality of deep penetration fillet welds should be determined by procedure testing before being used on a fabrication.

Metallurgical factors

Solidification cracks are formed at high temperatures, *i.e.* while the weld metal is solidifying or immediately afterwards.

Two principal metallurgical factors promote cracking of weld metal:

1. A wide solidification range, *i.e.* a wide temperature range during which the weld is in a mushy state without any significant strength or resistance to contraction stresses.

Pure metals such as aluminium, copper and nickel and alloys that solidify over a small temperature range are resistant to solidification cracking when welded with consumables matching the parent metal in composition.

2. The presence of low melting point films between the grain boundaries. These can be promoted by sulphur which forms sulphides in ferritic steel and in nickel or nickel alloy weld metal.

Welding consumables are designed to have a chemical composition and a metallurgical

structure that will resist solidification cracking provided that the geometrical factors discussed in the previous section are favourable. However, the composition of a weld is dependent on the dilution caused by mixing of the weld metal with that portion of the parent metal that is melted. Welding consumables should be selected that will tolerate the dilution that occurs in a particular joint design.

Stress

Stress on a welded joint arises from contraction of the weld while cooling and this shrinkage is opposed by the restraint of the component.

The stress on a welded joint depends on a number of factors such as section thickness, weld preparation and volume of weld metal and on the general stiffness of a fabrication.

Provided that the correct choices have been made of welding consumables, joint design, weld sizes and geometry it is possible to weld the most rigid structure without solidification cracking. This is fortunate because restraint is generally inherent in any structure and out of the control of the fabricator.

However, if the welding sequence is not carefully controlled the restraint in one part of a structure may increase during fabrication because of contraction of welds on other parts. A simple example is the angular distortion that takes place when a T joint is welded on one side and is free to move. If a weld is deposited on the second side while the first weld is shrinking the stress on the second weld may be increased sufficiently to cause cracking.

Similar conditions may occur in a butt joint that is free to move. The first weld run on the second side may crack because of contraction of the weld on the other side.

Therefore, prevention of distortion during welding may be an effective precaution against weld cracking and the following rules should be followed:

- use clamps, strongbacks, jigs and fixtures;
- use frequent tacking;
- use block welding to prevent movement.

Hydrogen cracks

Hydrogen induced cracking can occur in the heat affected zone (HAZ) or less commonly in the weld metal in steel fabrications.

When steel is welded the parent metal adjacent to the weld is heated to high temperatures and is subsequently cooled rapidly and this thermal cycle causes microstructural changes in the HAZ.

The extent of these changes depends on the composition of the steel and the rate of cooling during the thermal cycle. The rate of cooling depends on the section thickness and the heat input from the welding process and also the preheat if any. When the rate of cooling is high enough to be critical for the particular steel composition being welded a hardened HAZ is produced.

A hardened HAZ is susceptible to cracking if sufficient hydrogen is dissolved in the weld and diffuses into the HAZ. This form of cracking is known as hydrogen cracking, hard zone cracking or cold cracking.

Hydrogen cracking can occur at the toe of a weld, at the root, or it may be buried at any point

in the HAZ when it is sometimes referred to as underbead cracking (*Fig. 7*).

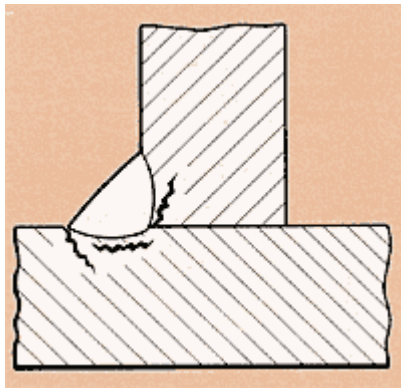


Fig. 7. Hydrogen cracks in HAZ of fillet weld

The conditions for this form of cracking to occur may be stated simply as sufficient hydrogen and a high enough stress, on a susceptible microstructure, at a temperature below about 150° C.

Under high restraint hydrogen cracks may also occur in weld metal and these cracks may be either longitudinal or transverse, occasionally occurring together.

Hydrogen cracking may be prevented by taking one or more of the following precautions:

- Use of a low hydrogen process such as MIG welding or manual metal arc welding with basic covered electrodes dried at high temperatures;
- Preheating of the parent metal before welding and maintaining the preheat during welding;
- Use of high heat input by deposition of large weld beads.

The practical application of the above precautions is described in BS 5135:1984 *Process of arc welding of carbon and carbon-manganese steels* and in AWS 131.1-90 *Structural welding code*.

Effects of geometrical and metallurgical factors and stress level are briefly as follows:

Geometrical factors

The main factors are section thickness and weld size.

Butt welds

The root run is generally made with a smaller weld bead than subsequent runs either to control penetration or because in manual metal arc welding it is necessary to use a smaller diameter electrode to obtain access to manipulate the electrode with the correct arc length. The small root run will have low heat input compared with the subsequent runs and it is essential to choose the initial preheating temperature to allow for this.

When the root run has been deposited some relaxation of the preheat may be possible but this should be confirmed by procedure testing.

Fillet welds

The first run in a multipass weld is generally made with the same size of weld bead as subsequent runs so the same preheat will be required throughout.

In both butt and fillet welds care should be taken with tack welding which can be subject to hydrogen cracking. Tack welds should be made having similar size to that of the root run and should be made under the same conditions of preheat if hydrogen cracking is to be avoided.

The only exception to this is when a deep penetration process such as submerged-arc welding is used, which completely envelopes any manually deposited tack welds and their HAZs.

Metallurgical factors

The microstructure and hardness of the HAZ depend on the percentage of carbon and alloying elements present. For structural steels such as those covered by BS 4360 the composition of the steel can be expressed in terms of a carbon equivalent formula and welding procedures to avoid cracking based on this formula are given in BS 5135. It is important to note that the carbon equivalent formula applies only to steels having a maximum CE of approximately 0.54% and a maximum carbon content of 0.3%. For medium carbon and low alloy steels the CE formula should not be used to determine preheating temperatures.

Welding procedures determined by BS 5135 to avoid HAZ cracking will generally prevent weld metal hydrogen cracking, but this again only applies to carbon-manganese steel weld metal normally used to weld structural steels. Higher strength low alloy steel weld metal, particularly Cr-Mo types, may require higher preheating temperatures than the parent metal to prevent hydrogen cracking.

As mentioned under solidification cracking, stress level is a function of section thickness, weld preparation, volume of weld metal and the stiffness of a fabrication.

It was explained that to prevent solidification cracking it is advisable to prevent movement of a component while a weld is being deposited. Once a weld has solidified and cooled to some extent solidification cracking is no longer a possibility, but in contrast hydrogen cracking can occasionally occur up to several days after welding is completed.

Therefore, to avoid hydrogen cracking either in the weld or the HAZ it is desirable to control distortion as far as possible until fabrication is completed.

When a large structure such as a bridge or an offshore platform is welded it may be impossible to prevent the build up of stress on a joint caused by the shrinkage of welds on another part of the structure.

This underlines the importance of making welding procedure tests realistic, so that the conditions of restraint match those in the component to be welded as closely as possible. All too often plates of similar thickness to those to be used in fabrication are set up quite free to move, preheat is applied and welding is carried out to produce crack free joints. Surprise is expressed when the subsequent fabrication requires extensive repairs.

The standard or code of practice used to approve welding procedures may allow tests on 25mm thick plate to qualify plate thicknesses up to 50mm but this may not prevent cracking of the thicker joint.

Appreciation of this limitation of welding procedure tests carried out according to a particular code should encourage the realistic design of qualification tests and should give increased assurance against cracking during fabrication.

The delayed nature of cracking should be taken into account when planning weld inspection procedures, so as to avoid inspecting too soon after welding with the associated risk of missing delayed cracks. It is for this reason that some standards recommend a delay time before

inspection of typically 24-48hr.

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