Steel Bridge Group Guidance Note

Hydrogen/HAZ cracking and solidification cracking in welds

No. 6.04

Scope

This Guidance Note gives information about a particular aspect of welding; the tendency for cracks to develop in the weld or the heat affected zone (HAZ) that would impair structural effectiveness and which could lead to failure.

Background

While the first welded bridge was constructed in the UK in the 1930's, the first British Standard on the subject was not published until the 1950's and its content was very basic. BS 5135, first published in 1974, was the first comprehensive standard on the subject and it included guidance on the avoidance of hydrogen cracking. That Standard has now been superseded and guidance on the avoidance of hydrogen cracking is now given in BS EN 1011-2.

Along the way many problems have been encountered and much research has been carried out. Welding is now one of the most widely used industrial processes and many excellent and extensive texts exist covering the jointing of many and various materials.

The problems are now very well understood, but for a busy supervising civil engineer not specializing in this area, there are few of these texts which give a simple insight to the basic issues which affect bridge construction.

This Note seeks to give that insight and put the reader in a position where some of the more complicated issues are perhaps not so daunting. Only the basic metallurgical issues are considered.

Hydrogen/HAZ cracking

The molten metal in a weld pool can take surprising amounts of hydrogen into solution from moisture and the atmosphere (see below). On cooling and solidification of the weld metal, hydrogen comes out of solution and migrates, some to atmosphere, but most across the fusion boundary of the weld into the parent metal.

If the metal in the heat affected zone (HAZ) of the parent metal, adjacent to the weld pool, has not become significantly hard during the welding process, then there is no particular problem. However, if significant hardness exists, the material in this region is more susceptible to cracking, and hydrogen migrating through such regions can find planes of weakness where it can exert very large pressures, which can lead to cracking. Cracks so induced can run in any direction.

Hydrogen will migrate quickly in hot metal, hence it will move rapidly from the weld pool to the adjacent heat affected zone of the parent metal, but thereafter, as this zone cools the fastest, its movement is retarded

The fastest cooling region is also the region that is likely to exhibit the hardest material. Therefore, hydrogen has a tendency to dwell in the region where it can do most damage, and any cracks which form may not be evident for many hours after welding.

To guard against such problems weld procedures should limit the hardness that may develop in the HAZ of the parent metal, or limit the amount of hydrogen that can get into the weld pool, or both.

Hardness in the heat affected zone increases with rate of cooling and with the amount of alloying in the parent material.

The amount of alloying in the parent material is expressed in terms of carbon equivalent value (CEV). A high CEV indicates that the parent material will develop considerable hardness if cooled quickly. A low CEV indicates low hardenability on rapid cooling.

The rate of cooling is directly proportional to the size of the heat sink provided by the parent material, (usually expressed as combined thickness), and is inversely proportional to the size of the weld pool.

The two main techniques of controlling the cooling rate are to increase the heat input into the weld pool (i.e. a bigger weld pool will cool more slowly than a smaller weld pool on the same joint), and to pre-heat the joint material before welding.

Obviously pre-heating the parent material will reduce the temperature differential to the weld pool and so reduce the flow of heat, but the more significant point about pre-heating is that it reduces the thermal conductivity of the parent metal and this has a much greater retarding effect on the flow of heat from the weld pool to the parent plate, so reducing hardness in the heat affected zone.

The other benefit of retarding the cooling rate is that it allows a higher proportion of hydrogen to migrate to atmosphere so reducing the flow of hydrogen through the heat affected zone.

Potential sources of hydrogen in weld pools can be: the type of flux used (which may contain hydrogen); moisture absorbed into the flux; damp or rusty electrodes; moisture on the joint surfaces; oil or grease on joint surfaces or consumable wire; the atmosphere (if the effect of shielding gases around the arc is reduced by excessive air currents).

Even with the best of practice, hydrogen will be present to some extent in the weld pool. Different processes and consumables give rise to their own levels of diffusible hydrogen. Advice is given in BS EN 1011-2 on the diffusible hydrogen levels that can be safely assumed for the commonly used welding processes. Exceptional cases can be assessed by test.

By balancing the above factors, (heat input, combined thickness, pre-heat, electrode classification, and the CEV of the parent material), and by using the tables in BS EN 1011-2, a weld procedure to avoid hydrogen cracking can be developed.

The essence of the matter is simple. Higher levels of hydrogen can be tolerated as long as the HAZ hardness is low, or higher levels of hardness in the heat affected zone can be tolerated as long as the amount of diffusible hydrogen is low. But the two cannot be tolerated together, especially if the restraint applied to the joint and hence internal stress is high.

If the level of hydrogen is too high, relative to hardness and restraint considerations, it is possible for delayed hydrogen cracking to occur. This may occur on the weld surface, at the heat affected zone or sub-surface, within the weld/parent material interface.

Such cracking may not occur until a significant time after the weld has cooled. Until more recent times, it was suggested that weld testing should be delayed for 48 hours to allow such cracks to occur. More discretion is now thought appropriate. BS EN 1011-2 (Ref 2) recognizes that the probability of hydrogen cracking in unrestrained thin material of low carbon equivalent is remote, while the probability in thick restrained sections of high carbon equivalent is much more significant.

Greater care should be taken with respect to delay in the case of the new higher strength steels (S420, S460), where experience is still limited and risks are higher. The discretion allowed in BS EN 1011 permits the delay time to be related to the particular joints, but caution should always be observed.

Solidification cracking

From the above explanation it would appear that high levels of heat input in the weld pool together with high pre-heat would virtually eliminate the possibility of hydrogen cracking.

However, if the weld pool cools too slowly, a phenomenon called solidification cracking can occur. Another contributory factor is material composition; particularly susceptible materials are those with higher levels of impurities such as sulphur and phosphorus.

Slow cooling rates give rise to the growth of large metallic crystals, but in addition non metallic substances present in the weld pool (which have considerably lower freezing points) can stay fluid long enough to gather and cause intercrystalline weakness in the weld metal. This, combined with high levels of internal stress as the weld cools, can give rise to solidification cracking.

This is a problem which can arise with welding processes using high heat inputs; for bridge construction today the process with potentially the highest heat input is submerged arc. This is not to say that the process is undesirable or of low standard, indeed, used properly the submerged arc process can deposit very clean weld metal of very high integrity and was a major step forward when generally adopted by bridge fabricators in the early 70's. But just as with any inherently high powered machine, it needs to be properly controlled.

The solution to the problem is to restrict grain growth and render the non metallic inclusions harmless.

Grain growth can be contained by avoiding very high heat inputs or heat build up, together with the use of weld consumables with grain refining alloys. The most commonly used grain refining addition is nickel.

The problem of non-metallic inclusions is normally contained by the addition of manganese, which combines with the non-metallic materials to render them less harmful.

Solidification cracking is found in the centre of the weld bead and runs longitudinally in the weld. It is often also referred to as centreline cracking.

The geometry of the weld bead also has a bearing on the matter. A weld bead where the depth of penetration exceeds the width generates more internal stress on cooling than a weld bead where the reverse is the case. High internal stress will increase the probability of solidification cracking.

Solidification cracks will occur as soon as the weld cools; as soon as the weld is fully cooled, testing for this defect can proceed.

Annex E of BS EN 1011-2 (informative) provides further guidance in avoiding solidification cracking.

Comment

To qualify as a welder in bridge construction, an operative is, regrettably, not required to have any knowledge or appreciation of the foregoing matters.

The more reputable fabricators take it upon themselves to give their welders some training and education in these matters.

As things stand, the quality of the welding supervisor in the factory or on site is the critical factor in ensuring that procedures are properly followed and in achieving the required standard.

References

1. BS 5135: 1984, Specification for arc welding of carbon and carbon manganese steels. (Withdrawn)
2. BS EN 1011-2:2001 Welding. Recommendations for welding of metallic materials. Arc welding of ferritic steels