Welding of High-Strength Steel

By V. G. PARANJPE*

In the last few years, the use of low alloy high-strength structural steels and also ultra high-strength structural steels has slowly increased due to the fact that several earth moving machinery manufacturing concerns have taken to these steels in view of the strength-to-weight advantage they get from these very sophisticated varieties of products. For earth moving machinery, as also for other transport vehicles, a reduction in dead weight is possible by the use of stronger steels and this enables the transport unit to be rated with an increased net carrying capacity without any change in the prime mover or other mechanical units. The use of high-strength steels also provides for wear resistance and therefore is particularly common in earth moving machinery like dumpers, dippers, bull dozers, tractors, etc.

To be competitive, however, high-strength steels have to be weldable as fabrication by welding is by far not only economical but also superior to the other outdated riveted and bolted structures. This condition imposes a restraint on the chemistry as well as properties that can be attained from high-strength steels since increase in strength normally reduces the ease with which the steels can be welded unless special precautions or special measures are adopted to counter the adverse effects.

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In view of the likely development of increasingly stronger and tougher steels it is proposed to discuss a few basic problems that one encounters both in the development of high-strength steels and their weldability.

What is a Good Weld

There are two important aspects of a good weld.

a. After welding, a sound joint has to be formed which is free from discontinuities like cracks, porosities, inclusions, etc, and

b. The joint formed after welding including the portion of the base metal which is affected by the thermal cycles introduced during welding should be able to withstand service conditions with the same reliability as of the base metal.

From the above principal considerations it is obvious that the electrode chemistry, properties of the electrode coating, or the special techniques used for sub-merged arc welding, T I G, M I G, electro-slag welding, etc. have to be all designed to ensure a sound defect-free weld. Use of low hydrogen electrode is one of the first basic requirements for obtaining good welds in high strength steels which are prone to hydrogen embrittlement and therefore cracking. Similarly the weld deposit should have corrosion properties exactly similar to or better than the base metal ; otherwise the weld which may be sound in other respects may fail during service conditions. These characteristics are to be ensured by the manufacturer of welding equipment, welding electrodes and welding fluxes.

The fact that the weld is free from H A Z (heat affected zone) cracking becomes the responsibility of the steel maker who designs the steel composition to ensure that the heat cycles introduced during welding do not lead to undue hardening of the heat affected zone as this is the basic reason for H A Z cracking. In steels with much higher strengths than those obtained in a normal as-rolled, as-rolled and normalised, or control rolled steels, another special effect is introduced during the thermal cycles of the welding operation ; this is not obvious adjacent to the weld but at some distance away where the weld heat temperatures have already quenched and tempered the structure to hardness levels and strength properties lower than those of the parent metal. Thus, the heat cycles in such cases do not lead to over hardening as is normally encountered in steels susceptible to H A Z cracking but introduce softening. The only method of minimising this deficiency is to regulate the heat input during welding so that undue over tempering does not take place.

Weldability Tests

Since the basic requirements of a good weld are outlined above, it is quite easy to lay down the various categories of weldability tests or tests which ensure that satisfactory welds can be made by choosing an appropriate combination of base metal and welding electrode. These categories are as follows :

(a) Tests for obtaining a satisfactory weld during fabrication. These in turn are of the following types :

(i) Underbead cracking test.
(ii) Restraint cracking test.
(iii) Porosity and inclusion test.
(iv) Hydrogen cracking test.

(b) Weldability for service performance.

(i) Bend test.
(ii) Tension test
(iii) Toughness test.
(iv) Fatigue test.

(c) Indirect tests such as weldability through examination of

(i) Metallographic structure.
(ii) Hardness.
(iii) Hardenability.
(iv) Transformation behaviour.
(v) Heat treatment by simulated operations.

That a plethora of tests have been developed by various research workers and development laboratories is obvious from the following detailed lists which have been collected from the literature.

I. Weldability for Fabrication

1. *Underbead cracking tests*

(a) Longitudinal bead weld cracking test.
(b) Circular bead weld cracking test.
(c) Reeve test.

2. *Restraint cracking tests*

(a) Lehigh restraint test.
(b) Naval Research Laboratory restraint test.
(c) Circular patch test.
(d) Focke Wulf test.
(e) Modified Reeve test.
(f) Double Tee fillet weld cracking test.
(g) Circular groove test.
(h) Navy 'Torture' test.
(i) C T S test
(j) Y Groove restraint cracking test
(k) Varestraint test.
(l) The Bollenrath test.
(m) The R D test.
(n) The O'Neill cracking test.
(o) Restraint fillet test.
(p) The Kommerel test.
(q) H Weld test.
(r) Brown Boveri Cracking test.

3. *Porosity and inclusion tests*

(a) Visual inspection.
(b) Radiography.
(c) Spot fusion test.

4. *Hydrogen cracking test*

(a) Constant load rupture test.

II. Weldability for Service Performance

1. *Bend test*

(a) Longitudinal bead weld notch bend tests.
(b) Transverse bead weld notch bend test.

(c) Tee bend test.
(d) Transverse butt weld notch bend test.
(e) Unnotched butt weld bend test.
(f) O N O R M bend test.
(g) Dutilleul test.

2. *Tension tests*

(a) Longitudinal bead weld notch tension test.
(b) Unnotched longitudinal bead weld tension test.
(c) Longitudinal and transverse butt weld tension tests.
(d) Double tee tension test
(e) Hatch corner tension test.
(f) Cruciform tension test.

3. *Toughness tests (Impact tests)*

(a) Dead weld impact test.
(b) Butt weld impact test.
(c) Butt weld explosion test (Explosion Bulge test).
(d) Delta test.
(e) Robertson test.
(f) C O D } Fracture toughness test.
(g) K I C tests. }
(h) Drop wt. test.
(i) Dutilleul test.
(j) Schnadt test.
(k) N R C test (Notch root contraction test).

4. *Fatigue test*

III. Indirect Tests

1. Metallographic examination.
2. Hardness.
3. Hardenability.
4. Transformation behaviour determinations (Rapid dilatometer).
5. Heat treatment simulating welding (weld simulating test).

Basically it is not essential that all the above tests be performed. Unfortunately, however, the various tests that have been developed have found their way into literature and certain people have developed confidence only in a particular series of tests and are not willing to accept, unless convincing arguments are put forth, that an alternative test may be equally satisfactory. We would like to take this opportunity to urge the members of this seminar to take a rational view and try to evolve an agreed list of a few minimum types of tests that should be sufficient to convince both the manufacturers of special steels, the manufacturers of electrodes and the consumers that a particular steel composition and electrode make can give satisfactory welds. There is a great need for evolving such an agreed list of weldability tests because even arbitrary weldability indices are based again on several formulae which vary from country to country. Unless an agreed list is evolved at an early date the development of special high-strength steels for welded construction is likely to suffer a severe set back because it would then be necessary to subject such steels to numerous tests, perhaps quite unnecessary, before a manufacturer can successfully market a new weldable high strength composition.

Weldability of As-Rolled High Strength Steels

The standard high strength composition satisfying the IS : 961 St 55 HTW, is just on the border line of good weldability because it contains quite high concentrations of manganese and chromium. There are alternative high strength compositions using titanium and nitrogen as alloying elements which are being patented by the Steel Company which offer more ease in welding as the hardness developed in C T S tests does not exceed 290 VPN.

Generally steels with yield strengths upto 40 kgf/mm² can be considered easily weldable if the total carbon equivalent according to the British Standard Specification BS : 1360 does not exceed 41 or 45 as a maximum. The carbon equivalent is calculated by the formula $CE = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}$.
Steels with higher strength have, however, to be subjected to either pre or post heating and this can present severe difficulties for fabrication in the field. The basic advantage of steels with limited strength, say upto 40 kgf/mm² yield, is that the base micro structure is that of fine pearlite in a ferritic matrix and the high strength properties are obtained through a smaller grain size rather than harder microstructure. Dispersion precipitates particularly of nitrides and carbides like VN or TiN or CbC, etc. are also responsible for giving high strength without adversely affecting the weldability. The Mn-V steel developed by the Steel Company with guaranteed yield point of 45 kgf/mm², tensile strength of 60 kgf/mm² min. and elongation of 20% min. on the standard ISO gauge length, has guaranteed weldability upto 63 mm thickness. This has been effectively used by several manufacturers to take advantage of high strength and ease in fabrication.

Weldability of Control Rolled Steels

Here again the precipitation of Cb and V compounds like carbides and nitrides during the process of control rolling is responsible for the higher strength of these steels. Mechanical working is continued while the precipitation is taking place and therefore recrystallisation or grain growth is avoided. Thus one gets extremely fine grain size in the range of ASTM No. 9 or higher. The steels are not normalised after control rolling as this in fact would be harmful.

The welding of control rolled steels can be difficult in thicker sections as over heating of the adjacent base material can cause grain growth and agglomeration of the finely dispersed precipitates. To prevent this, heat input has to be restricted, or only thin sections should be utilised. The exact value of heat input has to be determined for every steel.

For the Mn-V-N control rolled high-strength steels developed by the Steel Company there is no difficulty whatsoever in welding of plates upto 12 mm thickness and this is the maximum size in which the product is at present put in the market. In C T S assemblies made entirely out of 12 mm thick plates the maximum hardness does not exceed 280 or 285 VPN and there is no damage to the microstructure nor is there any tendency towards H A Z cracking.

Welding of Weather Resistant Steels

Copper bearing steel compositions of medium and high strength steels have been specially developed by various countries to afford resistance to atmospheric weathering. The steels do get tarnished during exposure, but ultimately develop a weather-coat which prevents further weathering. The weather-coat is tightly adherent, non-porous and has an aesthetically pleasing dark patina colour. The steels can be used for out door construction in the unpainted condition ; in fact this is one of their most attractive properties in addition to high strength.

Since a minimum of .30 or in some cases a maximum of .75% of copper is the essential ingredient responsible for weather resistance, welding of such steels should normally be done by using copper bearing electrodes, so that no patches of a different shade develop in the weld region. If non-copper containing electrodes are used, the welding procedure should be designed to give maximum washing-in of copper from the base metal to the weld continuously so as to get as close a colour match as possible. This is achieved by using a single pass manual weld, preferably that of weave bead technique to provide more undercut.

Since the carbon content of these steels is generally limited, the basic weldability of the steel is quite satisfactory and little problem is encountered on this account.

Weldability of Quenched and Tempered Steels

During the last few years several manufacturers of earth moving and specialised equipment in India have based their fabrication programmes on quenched and tempered steels like the USS T 1. The ASTM specification A 514 and 517 cover the basic requirements of such steels for structural and pressure vessel applications. The minimum yield strength required is about 70 kgf/mm² and the tensile strength is of the order of 90 to 100 kgf/mm² with about 12 to 14% minimum elongation on the standard ISO gauge length. Low alloy low carbon steels can attain these property requirements in the fully quenched and tempered conditions, the tempering temperature being of the order of 600 to 630°C.

As indicated earlier the welding of these steels pose an entirely different problem, viz., softening of the base steel due to excessive tempering as a result of thermal cycles introduced. The only method of correctly specifying the welding technique is to assess the maximum heat input permissible without causing undue softening of the base metal. Once the maximum heat input is determined the welding parameters like electrode size, current and voltage setting and rate of electrode have to be fully specified so as to ensure that actual heat input does not exceed the permissible value.

Special indirect tests like end of transformation behaviour or the use of weld heat cycle simulator have been developed for assessing the maximum permissible heat input that a particular section and steel chemistry can stand without requiring pre or post heating. At present there are no facilities with any manufacturers of steel or welding electrodes to assess the correct welding parameters for the quenched and tempered steels in this country due to the simple reason that such steels are not being produced indigenously. However, it is quite apparent, that in order to keep abreast of advancing technology, steps in this direction are essential and this would require a very close collaboration between the manufacturers of steel, manufacturers of electrodes and equipment and consumers. Here is one more field where we would urge very active cooperation and close participation from all concerned.